OPTIMIZING IRRIGATED HORTICULTURE AND PREDICTION OF CLIMATE CHANGE IMPACTS BY CROP MODELING FOR NIGER

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CHAPTER I

INTRODUCTION

1.1. General information about Niger

Niger is a landlocked nation located in the Sahelian zone of West Africa, along the boundary between the Sahara desert and Sub-Saharan Africa. It extends between latitudes 23°N - 12°N and longitudes 0°E - 16°E. The country is bordered by Libya and Algeria to the North, Chad to the East, Nigeria and Benin to the South, and Burkina Faso and Mali to the West. Niger has an area of 1,267,000 km^2 with 2/3 of that area covered by the Sahara desert. The capital city, Niamey, is located in the west of the country. Niger consists of eight main administrative regions, which are divided in sub-regions and districts.

According to the United Nations Population Fund (UNFPA) (2008), the Niger's 2007 population was estimated at 13 million with an annual growth rate of 3.3 %. The fertility rate is one of the highest in Africa at 7.2 children per woman; and 66 % of the population is less than 25.

Niger's climate is hot and dry with a short rainy season from June to October, and a long dry season from November to May. The rainfall regime is characterized by high spatial and temporal variability, which is driven by the West African Monsoon (Tearfund, 2008). Hess et al. (1995) and Bello (1996) have found variability of the yearly total precipitation ranging between 20 to 80% for the Sahel Savannah including Niger. There is a noticeable decreasing gradient of the rainfall regime from the south towards the north of the country. Indeed, the mean annual rainfall varies from 824 mm at Gaya in the Southeast to 15.9 mm at Bilma in the Northeast (DMN, 2011).

The National Council of Environment for Sustainable Development (Conseil National de l’Environement pour un Devéloppement Durable) (CNEDD, 2006) reported in the National Adaptation to Climate Change Plan of Actions (NAPA) that the spatial distribution of rainfall has defined four climatic zones in Niger. The Sudano-Sahelian zone in the southwest is characterized by a sub-humid climate with an annual rainfall around 700 mm. The Sahelian and Sahelo-Saharian zones in the center are dominated by steppe vegetation and have an annual rainfall ranging from 600 to 150 mm. The Sahara zone, covering the largest part of the country, has a desert climate and a total rainfall less than 150 mm/year (Figure 1).

The mean daily temperature fluctuates through the year, with the highest temperatures in April and May while the lowest are recorded in December and January. The temperature also undergoes high diurnal variation which varies according to the location and the season. Niger’s climate constraints have resulted in frequent episodes of drought that greatly affect the agriculture activities.

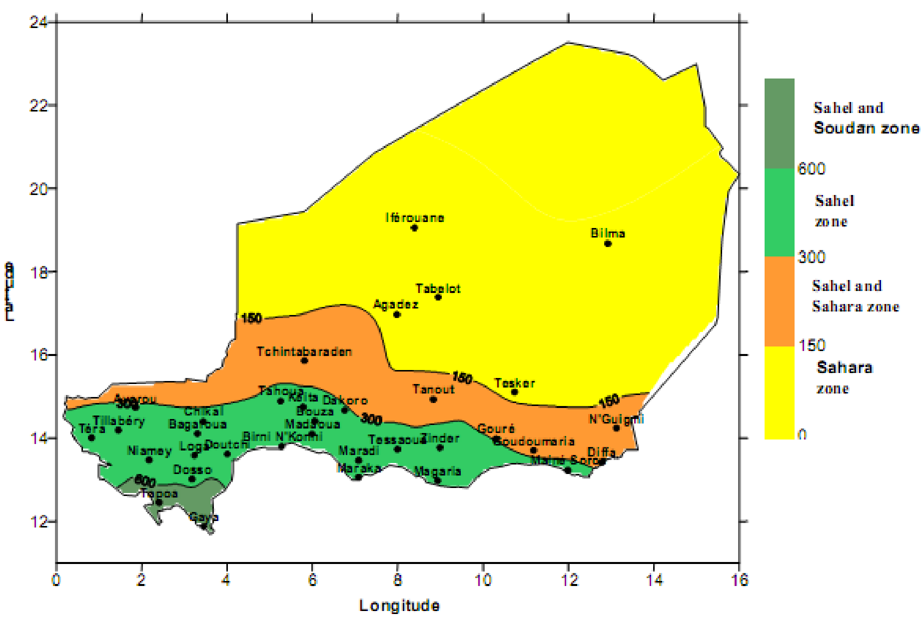


Figure 1: Climatic zones in Niger based on average rainfall over the period 1975-2004 (Source: National Meteorological Service of Niger).

Even though Niger has been facing recurrent drought events that have affected water bodies, it still possesses enormous ground and surface water resources. The most important surface water source is the river Niger, the third longest river in Africa, which spans a distance of 550 km in the western part of the country. Seven tributaries drain water into the river Niger along the portion of its pathway crossing the country. Two seasonal streams, the *Goulbi* and the *Komadougou Yobe* in the South and in the Southeast respectively, Lake Chad, and many ephemeral ponds are also part of the hydrographic network. According to NAPA (2006), the ground water is renewed at the rate of 2.5×10^{9} m^3 per year while the surface water renewal rate is 3×10^{10} m^3. The non-renewable ground water is estimated at 2×10^{12} m^3. The Food and Agriculture Organization (FAO) has reported that shallow groundwater is exploited in many areas for small garden irrigation in many African countries including Niger (FAO, 1986).

The economy of Niger depends on the exportation of uranium and some agricultural products including onion, cowpea, sweet pepper and livestock. The country's Gross Domestic Product (GDP) was estimated to $5.4 billion in 2009 (World Bank, 2011) with an annual economical growth rate of 3%.

Agriculture and livestock breeding represent the most important economic activities in Niger accounting for 41% of the country GDP (World Bank, 2011) and employing about 85% of the active population (FAO, 1996). Food crops include millet, sorghum, cassava, rice, sugar cane, and vegetables. Major cash crops are onion, cowpea, and sweet pepper, while lesser cash crops are groundnut and cotton. Livestock comprises camels, cattle, sheep, goats, donkeys, horses, and poultry.

Agriculture systems in Niger are characterized by small farms, of 5 ha or less, that cannot provide returns on large investments. Therefore, there is little mechanization and mineral fertilizer use, especially in rainfed agriculture. Relying mainly on traditional techniques, local rainfed agriculture is very sensitive to the highly variable precipitation patterns. The rainfed crops are mainly millet, sorghum, and cowpea. In addition to the rainy season cropping system, irrigated crops are cultivated during the dry season. The decline in the rainfed system over the last few decades has resulted in the expansion of the irrigated agriculture of rice and horticultural crops.

Despite the increasing interest in dry season irrigated agriculture, irrigation is still practiced in Niger with traditional techniques that may not guarantee efficient production and environmental sustainability. Improved water resources management is a requirement to reverse the trend and to be prepared to deal with the coming climate change.

To optimize horticulture production, decision-support tools such as a crop models are helpful to determine optimal planting, harvesting, and irrigation management strategies. So far, the agrometeorological models used in Niger to assist farmers and decision makers have only addressed rainfed crops. Therefore, modeling of irrigated crops may help the country's farmers to better manage irrigation water for a sustainable vegetable growth, and may add value to the efforts to address food security issues. Finally, knowing in advance the probable effects of climate change may help policy makers in the development of adaptation strategies.

1.2. Objectives

1.2.1. General objective

This study aims to develop decision-support information for irrigated horticulture in Niger based on weather, crop, and soil data in the context of a changing climate. The decision-support information includes the optimum planting periods, the recommended crops' irrigation water needs on a 10-day time step basis, the probable responses to climate change and a sketch of coping strategies.

1.2.2. Specific objectives

The specific purposes of this research are:

- Assessment of irrigation water requirements and optimum planting periods for the growth of potato, onion, tomato, sweet pepper, and cabbage in Bonkoukou, Galmi, Keita, Diffa, and Niamey respectively. The importance of those crops in the corresponding sites in terms of production and the areas they occupy has motivated the choice of these crop/locations combinations.
- Analysis of future climate change in the study areas and its impacts on the horticultural crops of interest.

CHAPTER II

REVIEW OF THE LITERATURE

2.1. Overview on the estimation of horticultural crops irrigation requirements in Niger

The decline in rainfed agriculture in some areas of the world due to the fluctuations in rainfall patterns has stimulated interest in the growth of dry season irrigated crops. To guarantee the sustainability of that type of agriculture, careful irrigation management is necessary under semi-arid regions such as Niger where the water resources are scarce. Indeed, Niger is a landlocked country located in the Sahelian zone of West Africa. The climate is hot and dry with a short rainy season from May to mid-October and a long dry season from mid-October to April. According to Lebel and Ali (2009), the rainfall pattern which showed an annual total between 300 and 400 mm during the wet period 1950-1969 had displayed a decreasing trend for years from the 1970s until the end of 1980s. They reported a generalized rainfall deficit of around 25–50% within that period.

Crop water demand is usually estimated based on the reference evapotranspiration (ETo) and the crop coefficient (Kc) values. There are several models to calculate ETo using climate data. Most of them have been tested in many locations in the world. Several studies (Dehghanisanij et al., 2004; Kashyap et al., 2001) have investigated their validity under semi-arid conditions and have found the Penman-Monteith approach to be the most suitable for semi-arid zones.

The crop coefficient varies as a function of the climatic conditions, the type of crop and the growth stages. Dooremboss and Pruitt (1977) proposed generic Kc for several crops in various climatic zones which can be used for a given location after calibration. However, less research has been done on Kc calibration in semi-arid areas. Wallace et al., (1993) attempted to calibrate the Kc values for rainfed millet in Niger using field crop evapotranspiration measurements and found an unsteady dynamic of Kc during the growing season. Kashyap et al., (2001) proposed calibrated values for potato Kc in a sub-humid zone which were 0.42, 0.85, and 1.27 for initial, development, and reproductive stages respectively. Mermoud et al., (2005) have adapted onion crop coefficients from Doorembos and Pruitt (1975) for Burkina Faso (similar climatic conditions as Niger) and found 0.7, 0.7-1.05, 1.05, 1.05-0.75 for initial, crop development, mid-season and late season stages respectively.

Horticultural crops are mainly cash crops grown during the dry season to combat food shortage related to the rainfall decrease in the country. The dry season vegetables and root crops include onion, pepper, cabbage, lettuce, tomato, eggplant, cucumber, carrots, potato, sweet potato, and cassava. The most important in terms of production are onion, tomato, cabbage, potato, and sweet pepper. The last census of agriculture and livestock estimated their production to 561×10^3 t, 43×10^3 t, 36×10^3 t, 19×10^3 t, and, 18×10^3 t, respectively (FAO/RGAC, MRA, and MDA, 2008).

Estimates of water requirements for those crops would help farmers avoid water wasting and financial loss related to the traditional techniques that are in use currently. Improved water resources management would promote efficient agricultural production and environmental sustainability.

Little is known about the irrigation water demand for dry season horticultural crops in Niger. Prashar et al., (1994) investigated onion evapotranspiration in Niger and concluded that the maximum water use occurs during the bulb formation when the onion water needs are around 7.5

mm/day. They observed also that trigging irrigation when the soil moisture available in the 20 cm depth had been depleted by 40% leads to better yield than the other strategies.

2.2. Climate change in Niger and horticulture

2.2.1. Climate projections for Niger

According to several studies compiled in the Intergovernmental Panel on Climate Change (IPPC) fourth assessment report (2007), temperatures are expected to increase in Africa as well as in most of the areas in the world. The predicted warming for Africa is likely to be about 1.5 times higher than the increase at the global scale (IPCC, 2007). Based on the A1B scenario and the projections of a set of 21 General Circulation Models (GCMs), IPCC (2007) reported that the median annual temperature increase for West Africa including Niger will be +3.3 ºC by the end of the century. While those climate projection models agree on the change in temperature, they remain inconsistent about the trend and the magnitude of rainfall variation in the Sahelian zone of West Africa (IPCC, 2007; Tearfund, 2008; CNEDD, 2009).

At the national level, the Niger second national communication on climate change (the latest national communication) reported performance test results of a sample of IPCC recommended climatic models (UKMO-HadCM3, MPI-ECHAM5, CSIRO-MK3, GFDL-CM2, and MRI-CGCM2). Although those models reproduce acceptably the unimodal and bimodal shapes of the annual variation of rainfall and temperature respectively, there is a time shift between the observed and simulated peaks (CNEDD, 2009). They reported also some discrepancies in the magnitude between the measured and the simulated values, and differences between projected values from one model to another. That behavior made them recommend caution in the use of those models' outputs and encouraged more investigation (CNEDD, 2009). According to the same report, the statistical downscaling of the models' outputs shows at the national level an increase in the annual mean maximum temperature of 2.3ºC (based on the scenario B2) and 2.6ºC (based on the scenario A2) for the 2020-2049 time horizon. Those annual temperature increases are +2.1 ºC, +2.2 ºC, +0.8 ºC, +2.5 ºC (scenario A2), and +2.0 ºC, +1.9 ºC, +0.9 ºC, +2.4 ºC (scenario B2) for Maïne Soroa, Birni N'Konni, Niamey, and Tahoua respectively.

2.2.2. Impacts of future climate change in relation with the horticultural irrigation water needs

Climate change has become a serious threat for food security in areas where agricultural production is very sensitive to meteorological conditions. Indeed the change in rainfall patterns combined with other environmental constraints such as soil degradation, plant pests, and diseases have contributed to decreasing crop production in semi-arid zones such as Niger where agriculture is mainly rainfed. More degradation of agriculture is expected to happen with the worse climatic conditions that have been predicted. Ben Mohamed et al. (2002) have estimated the reduction of rainfed millet production to 13% by the year 2025. Dry season irrigated agriculture is expected to be one of the most important measures to overcome that issue because of its lower sensitivity to climate compared to rainfed agriculture. Evidence of that situation has been shown by Kurukulasuriya et al., (2006) who conducted surveys in 2002-2004 across 11 African countries. They have found for Niger that the median net return per irrigated farm (around US \$1.2 $\times 10^3$/ha) was three times higher than the one from a rainfed farm (about US \$0.4$\times 10^3$/ha). Indeed, irrigated cash crop cultivation has increased and has contributed to mitigating the food shortage resulting from the poor rainfed agriculture production in drought prone areas of the country. However, the severe drought and higher temperatures predicted in semi-arid tropical regions would decrease the water availability for irrigation, while the crop water needs may increase due to the expected stressful temperatures and the higher evaporative demand. According to the FAO (2008), the irrigation areas in Sub-Saharan Africa will expand from 5.6 million ha in 2005/07 to 7.9 million ha by 2050. Consequently, irrigation water needs are expected to increase while water availability will decline. Therefore actions need to be taken now to mitigate the adverse effects of climate change in order to ensure the sustainability of that type of agriculture.

Several studies (Van Duivenbooden et al., (2002), Sivakumar, (1992), Salack (2006)) have been done on the implications of climate change in agriculture in the Sahelian region in general and in Niger particularly, using climate models outputs as inputs to crop models. However, studies implemented for Niger have focused mainly on the impacts of climate change on the yields of rainfed cereals and legumes. Little has been done on how dry season irrigated crops might be affected by future climate change in those areas.

CHAPTER III

METHODOLOGY

3.1. Presentation of study sites

Irrigation water requirements and yield were investigated for five horticultural crops in the Sahelian zone of Niger using crop models with historical and predicted weather data, soil and crop information. The five crops simulated were potato *Solanum tuberosum*, onion *Allium cepa*, tomato *Solanum lycopersicum*, sweet pepper *Capsicum annuum*, and cabbage *Brassica oleracea capitata*. Five specific locations were considered: Niamey, Bonkoukou, Galmi , Keita, and Diffa (Figure 2).

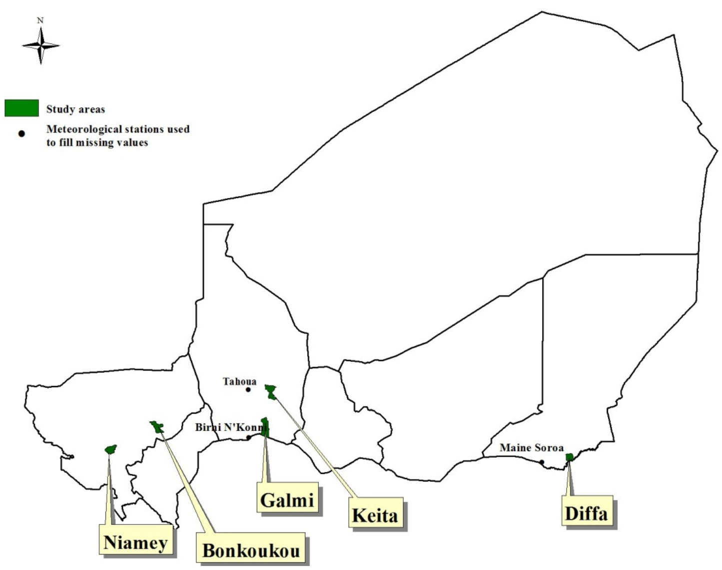


Figure 2: Study areas.

Source of sites geo-references: AGRHYMET and Google Earth
Source of base maps files: http://diva-gis.org/gdata.

The climate in the study sites is characterized in general by a short rainy season from May to early October and a long dry season from mid-October through April. The highest temperatures are recorded in April-May and the lowest temperatures in December-January.

- ***Niamey***

Peri-urban horticulture is widely practiced in the suburban area surrounding Niamey, Niger's capital. The area has an average annual temperature of 31°C with a mean annual rainfall around 500 mm (Figure 3). Only the irrigation water requirements of cabbage were analyzed for this location.

- ***Bonkoukou***

Bonkoukou is located about 130 km northeast of Niamey. It has a similar climate with less annual cumulative rainfall (400 mm) (Figure 4). It is one of the high potato production sites in the country, and therefore potato irrigation water needs were investigated for this location.

- ***Keita***

Keita is located in a valley zone 600 km east of Niamey, in the centre of the country. That location is characterized by a particular orography and a milder climate compared to the neighboring areas. Its relief is formed by several rocky plateaus separated by valleys, forming a complex and erosion-prone stream channel system. The annual mean temperature is 29°C and the annual rainfall is 430 mm (Figure 5). Tomato irrigation water requirements were investigated for that zone.

- ***Galmi***

Galmi is located in the south-central part of Niger. The annual rainfall is 490 mm and the mean temperature is 29°C (Figure 6). The Tahoua region, where Galmi is located, has the highest onion bulb production with about 49% of the national production. Onion represents the principal horticultural crop of the country and occupies 48% of the total area devoted to vegetables and root crops growth (FAO, 2008). Onion irrigation requirements were analyzed for Galmi location.

- ***Diffa***

Diffa is located in the eastern part of Niger, next to Lake Chad. The region is located on the border of the Tal desert and the upper limit of the Sahelian zone, and has a Sahelo-Saharian climate. The average annual rainfall is 290 mm while the mean temperature is 29°C (Figure 7). Despite the low cumulative rainfall, Lake Chad, and the Komadugu Yobe perennial stream represent important irrigation potentials for Diffa. There is also a system of small basins inside the oases that contribute to agricultural opportunities. Sweet pepper as well as other vegetable crops, rice, and wheat are cultivated in the Valley of Komadugu stream. According to the Regional Development Council (Conseil Régional de développement, CDR) annual report (CDR, 2006), the irrigation water is drawn generally from the stream through excavated earth channels on traditional farms or by concrete channels on modern managed lands. Then, it is pumped from the channels to the plots. Sweet pepper is the most cultivated vegetable crop in Diffa as 89% of the arable land used for sweet pepper production in the country is located there (FAO, 2008). Therefore, the sweet pepper irrigation water needs were analyzed for that location.

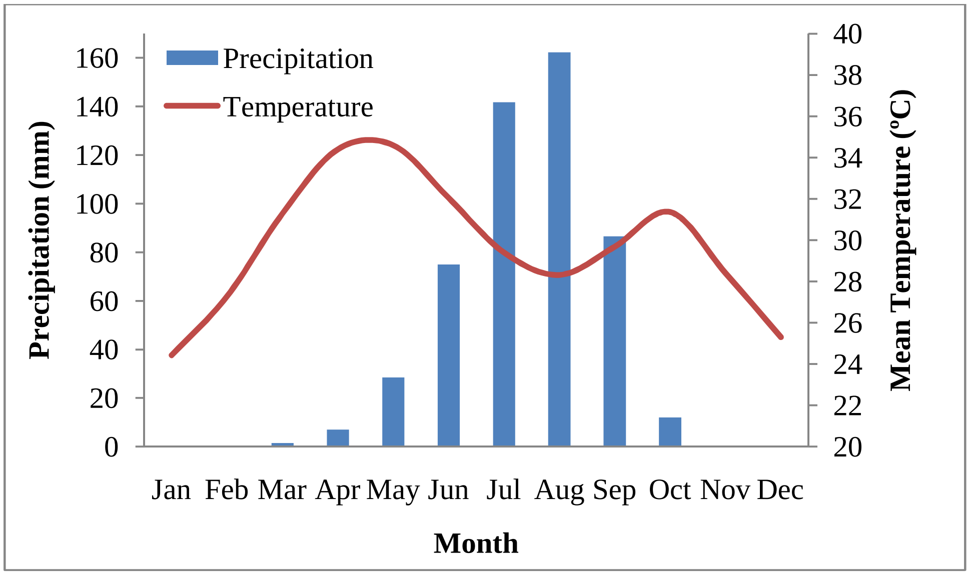


Figure 3: Monthly mean temperature and precipitation for Niamey.

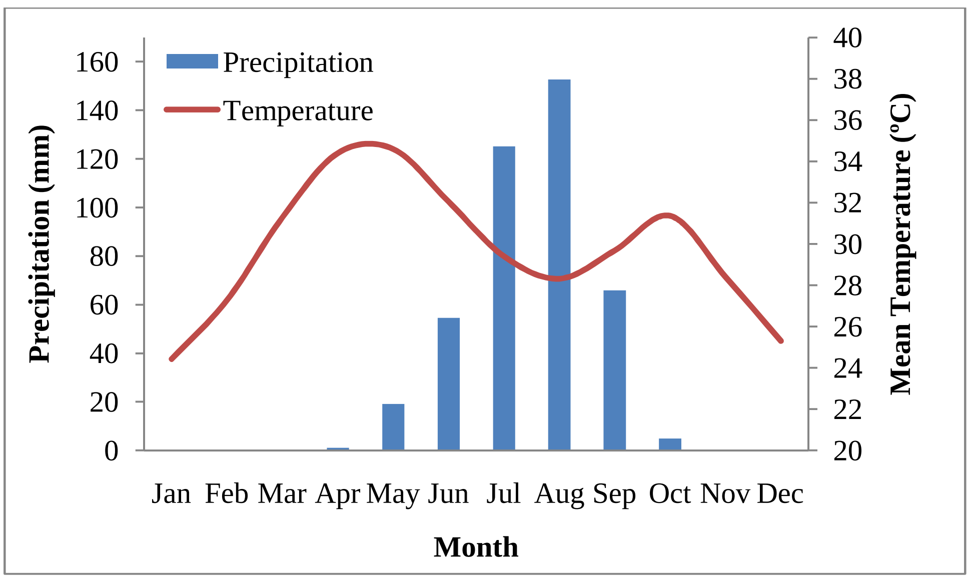


Figure 4: Monthly mean temperature and precipitation for Bonkoukou.

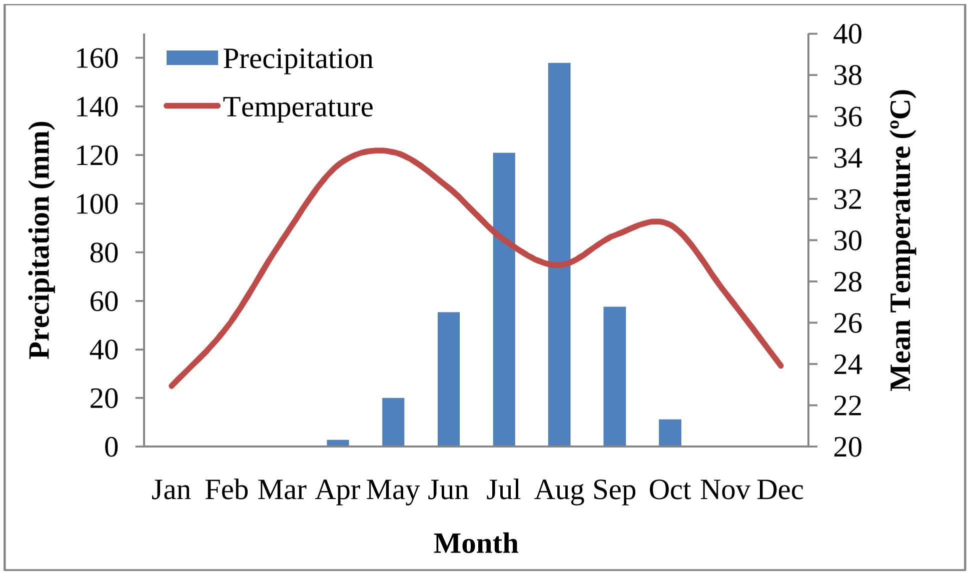


Figure 5: Monthly mean temperature and precipitation for Keita.

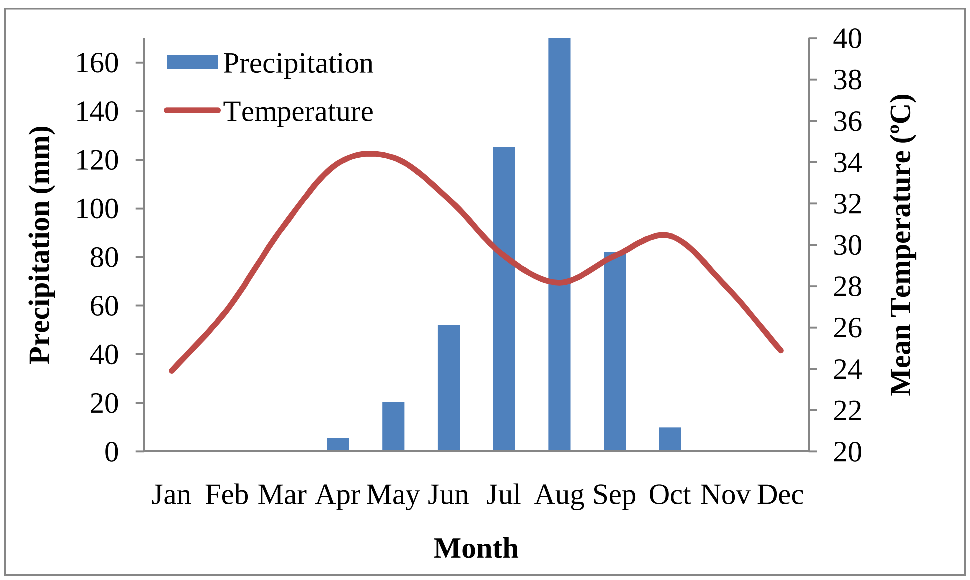


Figure 6: Monthly mean temperature and precipitation for Galmi.

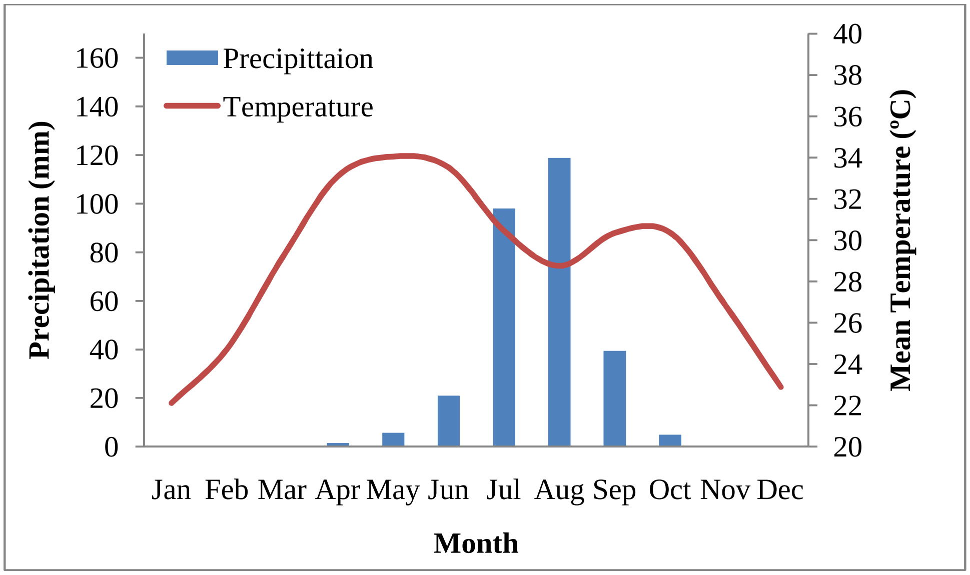


Figure 7: Monthly mean temperature and precipitation for Diffa.

3.2. Weather data

Historical daily weather data were obtained from the Niger National Meteorological Service (Direction de la Météorologie National) (Abdoulkarim Traore, head of the Service, personal communication, 2011) and include rainfall, sunshine, vapor pressure, maximum and minimum temperatures, maximum and minimum relative humidity, and 10 m wind speed. Only two sites, Niamey and Diffa, of the five stations have datasets comprising all the weather parameters. For the three other sites, Bonkoukou, Galmi, and Keita, only rainfall data are available. The other weather data used for those stations were collected from the nearest stations, which are respectively, Niamey, Birni N'konni, and Tahoua. The full dataset extends from 1961 to 2010 for all the sites except Diffa which dataset starts in 1986. Therefore, data from Maine Soroa station were used to complete the baseline1961-1990 used to generate the predicted data for Diffa. Relative humidity records are from 1990 to 2010 for all the stations.

3.3. Crop models

CROPWAT and DSSAT were used in order to have more complete outputs. Indeed DSSAT offers a large amount of outputs including crop growth and yields parameters which are not simulated in CROPWAT. However, the version of DSSAT used does not have parameters for onion while CROPWAT does.

3.3.1. CROPWAT

CROPWAT is a free computer program developed by the FAO Land and Water Development Division in the early 1990's to help agriculture water specialists in irrigation management (Kuo et al., 2006; FAO, 2011). This decision-support tool allows the estimation of reference evapotranspiration, crop water requirements and crop irrigation requirements. It may be used also to design irrigation schemes and assess the efficiency of irrigation practices. The background equations in CROPWAT for crop water and irrigation water requirement calculations combine the procedures in the FAO irrigation and drainage papers 24 and 33 titled respectively "Crop Evapotranspiration - Guidelines for computing crop water requirements" and "Yield response to water" (FAO, 2011). Therefore, the program uses climatic, soil, and crop data as inputs. One of the particularities of the model is its ability to use its own databases for climatic data and crop data when those data are not provided by the user.

Several studies have used CROPWAT in various applications related to irrigation and crop water use. Kuo et al. (2006) evaluated the irrigation water requirements for upland and paddy crops in Taiwan by the mean of that program. The Center for Environmental Economics and Policy in Africa (CEEPA) policy note No. 32 (CEEPA, 2006), based on Moussa & Amadou (2006), has reported the analysis of future climate change impacts on millet, sorghum, and cowpea water use and productivity in Niger using generated climatic data with CROPWAT.

3.3.2. DSSAT

Published for the first time in 1989, the Decision Support System for Agrotechnology Transfer (DSSAT), originated from the compilation of existing models such as the CERES models for maize, the SOYGRO model for soybean and the PNUTGRO model for peanut (Jones et al, 2003). It was developed by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project. Since then, DSSAT has undergone many improvements in its design that made it a group of models that consist of a series of independent modules working together. This on-going development is carried out within the collaboration of scientists from several US and Canada universities including the University of Florida, the University of Georgia, the University of Guelph, the University of Hawaii, the International Center for Soil Fertility and Agricultural Development, the Iowa State University and International Consortium for Agricultural Systems Applications (ICASA) (ICASA, 2011).

Each model is specific to a given crop or designed for the evaluation of an environmental characteristic including soil water content, soil organic matter, weed management, and nutrient management. Figure 8 from Jones et al., (2003) shows an overview of the DSSAT cropping System Model (DSSAT-CSM). For soil water simulation, DSSAT crop models use the 'tipping bucket' approach. The ability to generate weather data constitutes one of the unique features of the DSSAT system. Indeed the weather module in DSSAT can read and generate daily weather data that are used by other modules (Jones et al., 2003).

The DSSAT models use as inputs weather parameters (radiation, air temperature, rainfall, relative humidity, and wind speed), crop management data (crop, cultivar information, genetic coefficient, planting date, planting spacing, fertilization), soil data (soil moisture and soil nitrogen/carbon/phosphorus at different depths over time) and some other crop environment data depending on the purposes of the simulations. DSSAT also uses initialization data including previous cropping information, economical data, and management information (harvest and irrigation schedule). For models evaluation, DSSAT uses phenological stages information in addition to the common used crop data. The modular structure of DSSAT allows it to simulate a large amount of outputs as each of the modules generates data. The outputs of interest in the present study are the soil water balance results, the crop yield, and the crop growth length.

The DSSAT crop models are applied in various domains such as research, education and management. Examples of applications are generally crop management, water balance, climate impacts/change/variability, land use studies, fertilizer management, pest management, and yield forecast. DSSAT models have been tested worldwide and the most recent version of the software is version 4.5 which is still under development. Jones et al., (2003) have classified more than 100 studies conducted within five continents according to various applications of the system. Among recent DSSAT assessment for irrigations applications are the studies conducted by Guerra et al. (2007) and Yang et al. (2010) who used this family of models to investigate the irrigation water requirements for cotton in the coastal plains region of Georgia and wheat, maize, cotton, vegetables and fruit trees in North China respectively. The later study resulted in irrigation water estimates higher than the official statistics data, while the former results showed a good agreement between observed and simulated data during the growing season. Due to the huge number of crops considered and the range of input data required.

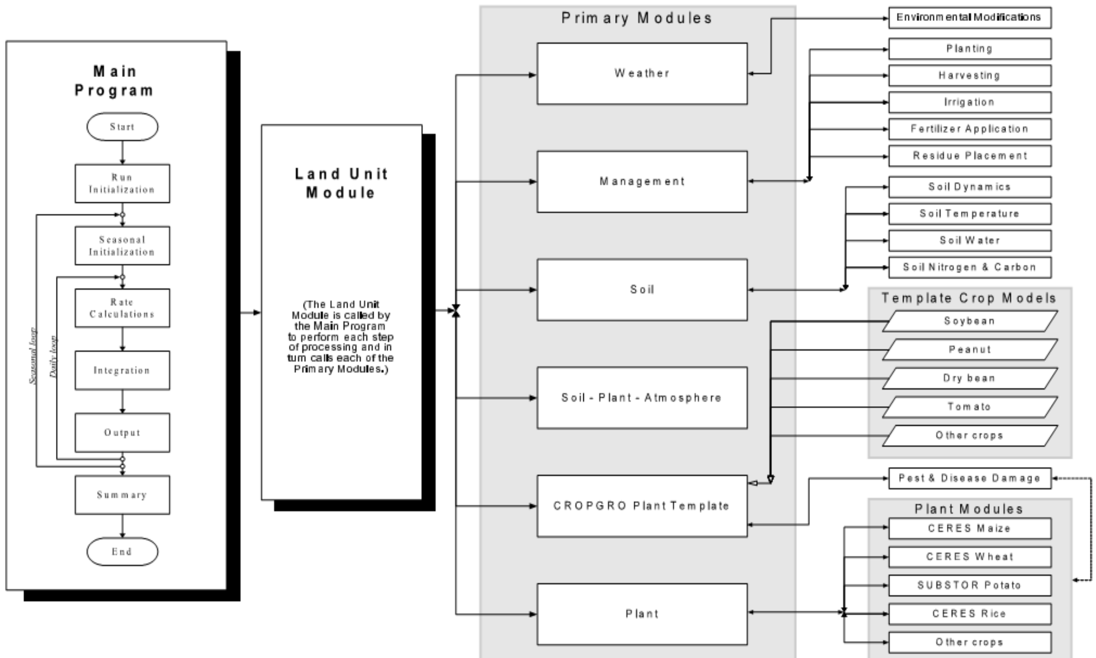


Figure 8: Overview of the components and modular structure of the DSSAT-CSM (Jones et al., 2003).

3.4. Climate change projection scenarios and generation of future climate datasets

3.4.1. GCMs and GHG emissions scenarios

The General Circulation Models (GCMs) have been established by several climate centers around the world, and are used in combination with CO_2 emissions scenarios to predict the future climate. In general, the GCMs generate the change in temperature and precipitation at a global/regional scale and on a monthly/annual basis. Then a spatio-temporal downscaling procedure is required to generate the future climate data at a given location. Lenart (2008) has described three main groups of climate change downscaling techniques: statistical, dynamical, and sensitivity analysis methods. The statistical downscaling methods derive the regional predicted climate variation from the global climate conditions predicted by the GCMs by using a set of equations. The dynamical approaches convert the GCMs global outputs at regional scale by adjusting them to the local meteorological numerical models. The third method is a group of approaches that infer the impacts of the GCMs global predicted change on a specific sector or business at a lower scale. Lenart (2008) gives preference to the statistical method because it allows using the “ensemble average” GCMs in the downscaling process, which means using the average outputs from several models as recommended by climate change modelers instead of a single model.

For the purpose of this study, we have used the outputs of the “ensemble average” approach from the “ClimateWizard” web-based program (climatewizard.org, 2009). Selecting that option in the program will pull out the 50^{th} percentile or median prediction, of all the 16 GCMs embedded in the program for a given location. As presented on the climate wizard website (www.climatewizard.org), the 16 GCMs included in that “ensemble average” system and their origin are listed in Table 1.

Table 1: The 16 climate models in the “Ensemble Average.”

CMIP3 I.D.	**Originating Group(s)**	**Country**
BCCR-BCM2.0	Bjerknes Centre for Climate Research	Norway
CGCM3.1(T47)	Canadian Centre for Climate Modeling & Analysis	Canada
CNRM-CM3	Météo-France / Centre National de Recherches Météorologiques	France
CSIRO-Mk3.0	CSIRO Atmospheric Research	Australia
GFDL-CM2.0	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA
GFDL-CM2.1	US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA
GISS-ER	NASA / Goddard Institute for Space Studies	USA
INM-CM3.0	Institute for Numerical Mathematics	Russia
IPSL-CM4	Institut Pierre Simon Laplace	France
MIROC3.2(medres)	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan
ECHO-G	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group	Germany / Korea
ECHAM5/MPI-OM	Max Planck Institute for Meteorology	Germany
MRI-CGCM2.3.2	Meteorological Research Institute	Japan
CCSM3	National Center for Atmospheric Research	USA
PCM	National Center for Atmospheric Research	USA
UKMO-HadCM3	Hadley Centre for Climate Prediction and Research / Met Office	UK

Source: (Climatewizard.org, 2009).

Temporal and spatial resolutions and other detailed information about those GCMs are available on line (www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php), the website of the Program for Climate Model Diagnosis and Inter-comparison Coupled Model Project (CMIP3).

The GCMs were run based on future greenhouse gases (GHG) emissions scenarios recommended by the Intergovernmental Panel on Climate Change (IPCC) in its Special Report on Emissions Scenarios (SRES) (IPCC, 2000). The SRES report is the IPCC approved version of the work done by Nakicenovic (2000) who has summarized 40 emissions scenarios, developed by five modeling groups, in four families (A1, A2, B1, B2) corresponding to four storylines with the same respective names (i.e. A1, A2, B1, B2) (see Figure 9 for more details). The storylines were defined according to socio-economical, environmental, and technological considerations. They relate the GHGs emissions driving forces (agriculture, land use, energy, economy, technology, population) to their evolution (IPCC, 2000). IPCC has described the four storylines in the SRES report as follow:

A1: A future world characterized by a rapid economic development, a low population growth, and a rapid and efficient technology development. In that world, more importance is given to personal wealth rather than environmental quality.

A2: A differential world with high population growth and where people give more attention to regional cultural identities, family values and local traditions, and less interest to a rapid economic growth.

B1: A convergent world where importance is given to clean development technologies and where people adopt concerted and global solutions to insure the sustainability of the environmental and social development. The dematerialization of the economy is also promoted in that world.

B2: A heterogeneous world in which it is believed that local solutions and community initiative are more likely appropriate than global solutions to achieve socio-economical and environment sustainable development, with a less rapid change with various technologies.

IPCC (2000) distinguishes, in the SRES report, six groups of scenarios deriving from the four families (Figure 9). Hence, according to the technological emphasis, the A1 family has been subdivided in three groups of scenarios which are A1F1 (fossil intensive), A1T (predominantly non-fossil), and A1B (balanced across energy sources). Each of the three remaining families is represented by a group of scenarios which has the same name than its originating family (i.e. A2, B1, and B2). The scenarios used in the ClimateWizard program are B1, A1B, and A2, corresponding respectively to a low case, moderate case, and high (worst) case GHG emissions scenarios (Figure 10 from IPCC 2007).

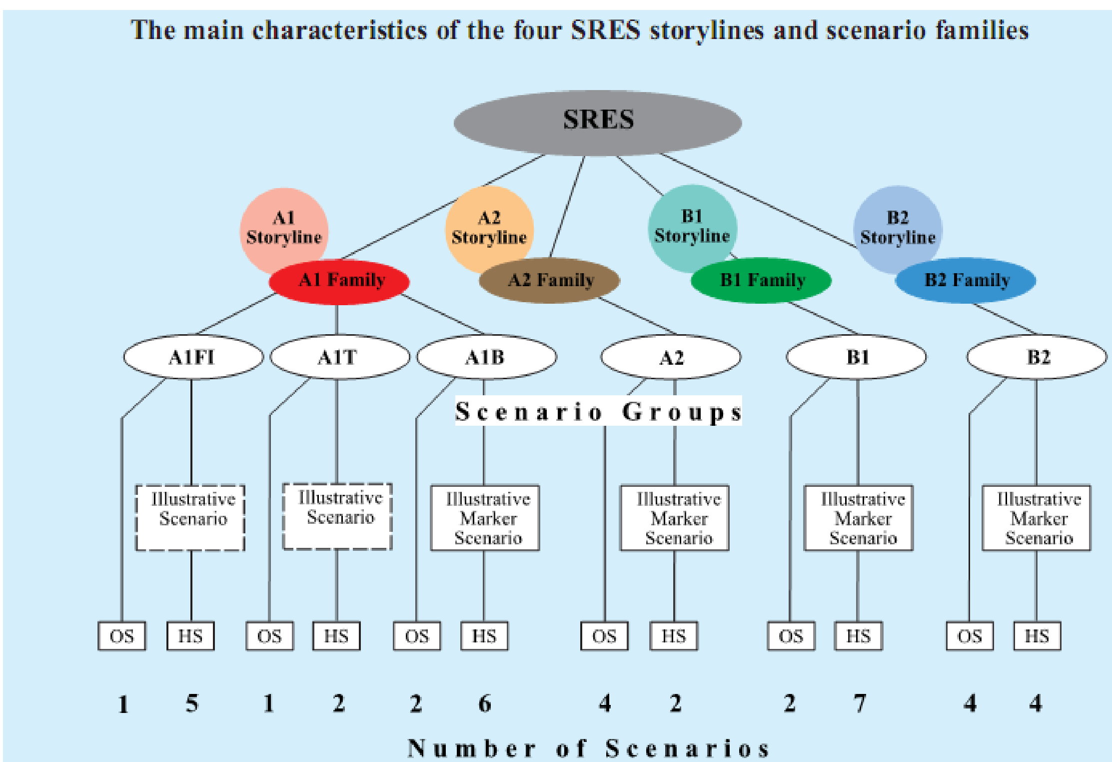


Figure 9: Schematic illustration of SRES scenarios (IPCC, 2000).

Three of those scenarios (A1B, A2, and B1) are available in the ClimateWizard program. Through the present work, the GCMs were run on the basis of the scenarios A1B and A2 respectively for the mid-century and end-century time horizons. The similarity of results provided by the three scenarios at mid-century (Figure 10) explains the choice to run the projections for that time line based on only one of them (A1B). Since B1 at end century gives comparative results with A1B at mid-century, and A1B at end-century leads to intermediate results between B1 and A2 (the worst case scenario) as it is shown in Figure 10, the scenarios B1 and A1B were neglected for the end-century projections.

The climate change predictions were performed only for temperature data. We assumed no change in rainfall trends. Justification for that assumption was the inconsistency of the climate models in rainfall prediction over the Sahel region. Additionally, the crops being studied are grown during the dry season, except for sweet pepper and onion, whose growing season may start in the rainy season. The possible impacts of the rainfall change on irrigation should be analyzed with regard to the irrigation water supply, which is beyond the scope of the present study. To summarize, the two scenarios used in this study to predict future climate change in Niger were:

- Scenario **S1**: No change in rainfall, A1B scenario & “Ensemble average” temperature change of 16 GCMs for mid-century;

- Scenario **S2**: No change in rainfall, A2 scenario & “Ensemble average” temperature change of 16 GCMs for end-century.

Considering the selected scenarios (Figure 10), the predicted change in the climate and its subsequent impacts on the crop irrigation water requirements discussed in the present research are based on the assumptions that there would not be any action to stabilize the GHG emissions at their current concentration level (2000 concentration level) and the future effects of possible local adaptation and mitigation actions have been neglected.

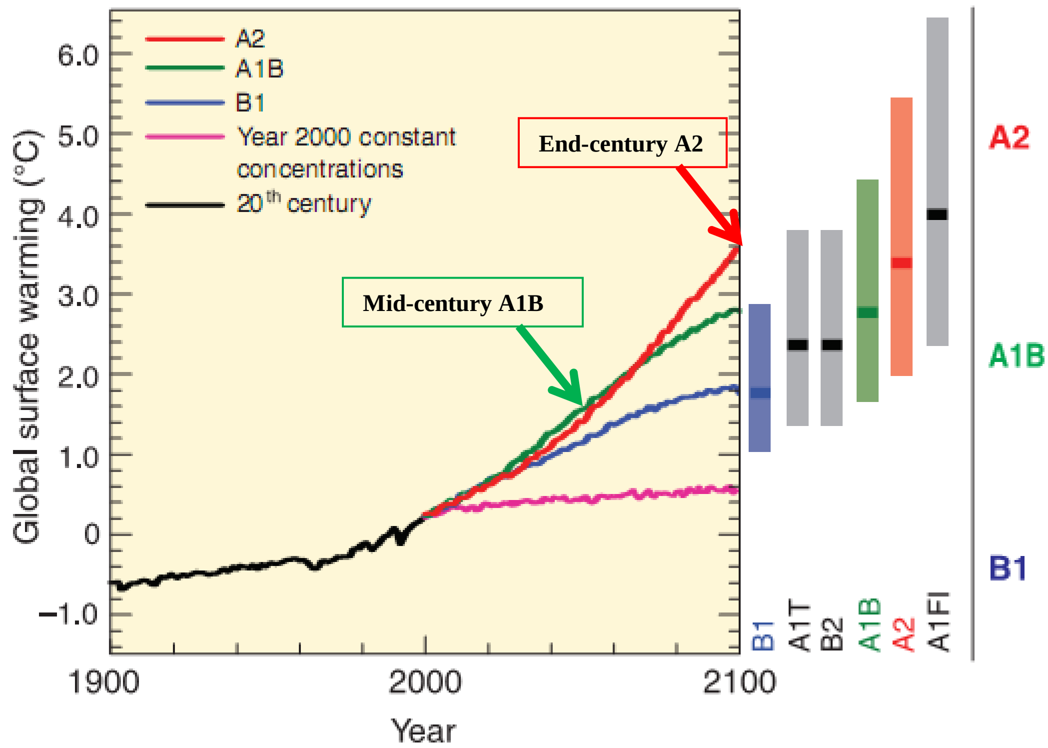


Figure 10: GHG emissions scenarios (modified from IPCC, 2007).

3.4.2. Generation of future weather data

Using the ClimateWizard web-based program, projections were made using the 1961-1990 period as the baseline. For each month of the year, the average change of monthly mean temperature was extracted for each of the five sites for the mid-century (2050) and end-century (2100) time horizons. In other words, for mid-century, the average predicted mean temperature change for a given month was obtained by averaging the predicted temperature change of the 16 models using the A1B scenario. The same procedure was repeated based on the scenario A2 for the end-century. The mid-century and end-century time lines correspond respectively to the periods 2040-2069 and 2070-2099 time periods (climatewizard.org, 2009).

The average predicted increases in mean monthly temperature (Table 2) were added to the daily observed minimum and maximum data from 1961-1990 to generate two datasets of future temperatures corresponding to 2040-2069 and 2070-2099 periods. For each of the sites, the generated temperatures were then used to replace the existing temperatures in the observed dataset of 1981-2010, the current climatic normal, which comprises rainfall, solar radiation, wind speed, sunshine duration, and mean relative humidity. At the end of the overall process, two projected climate datasets were thus generated corresponding to the mid-century and the end-century. Those data were used in the DSSAT and CROPWAT crop models to simulate the future irrigation water requirements for the five crops. Additionally, crop growth parameters, and yield were simulated by DSSAT for pepper, tomato, cabbage, and potato at the selected study areas. Since a model for onion is not supported by the DSSAT crop models system, the irrigation water requirements, for that crop were simulated using the CROPWAT model only.

Table 2: Average predicted mean monthly temperature change (ºC) by mid-century and end-century.

	Mid century - A1B					**End century - A2**				
Month	**Diffa**	**Niamey**	**Bonkoukou**	**Galmi**	**Keita**	**Diffa**	**Niamey**	**Bonkoukou**	**Galmi**	**Keita**
January	2.33	2.42	2.41	2.38	2.40	4.32	4.01	4.00	4.35	4.09
February	2.04	2.24	2.22	2.18	2.16	3.31	3.87	3.86	3.45	3.78
March	2.20	2.38	2.37	2.23	2.28	4.70	4.17	4.16	4.66	4.10
April	2.40	2.49	2.49	2.40	2.46	4.39	4.30	4.31	4.52	4.23
May	2.59	2.53	2.55	2.51	2.61	5.06	4.41	4.46	5.02	4.55
June	2.71	2.62	2.66	2.64	2.76	5.03	4.14	4.20	4.72	4.37
July	2.47	2.39	2.43	2.35	2.55	3.73	3.96	4.02	3.53	4.16
August	2.35	2.18	2.21	2.18	2.34	3.30	3.71	3.75	3.20	3.85
September	2.37	2.29	2.34	2.29	2.40	4.06	3.77	3.84	4.04	3.98
October	2.52	2.57	2.62	2.54	2.69	4.63	4.13	4.21	4.69	4.36
November	2.61	2.71	2.73	2.67	2.75	3.92	4.38	4.12	4.19	4.47
December	2.33	2.46	2.46	2.40	2.41	3.72	4.17	4.13	4.18	4.09

3.5. Procedures

3.5.1. Crop models evaluation

- ***DSSAT***

The DSSAT crop models system has been widely calibrated and validated for a large range of crops under several climatic conditions. However, the literature that has been reviewed during the present study does not show any similar work for horticultural crops grown in Niger. The purpose of this task is to attempt an assessment of the DSSAT performances in simulating the soil water balance and crop parameters for potato, cabbage, tomato, and sweet pepper. However, because of the lack of measured soil water parameters, the evaluation of the DSSAT soil water module has not been implemented.

Additional to the climate data, field measurements available to evaluate the models performance were mean crop yield at the district level, and limited information on the soils, planting periods, use of fertilizers, and irrigation practices. Those data were collected through literature and FAO on-line sources. Therefore, the crop input files were built based on that information and the soil input file were chosen from the DSSAT default soil profile based on the FAO HWSD soil classification. Simulations were run in relation to the years those data were collected. Then the simulated values were compared to the measured yield by calculating the bias errors between them. The RMSE and a linear regression were computed for sweet pepper, which had a longer series of measured dry yield. In order to match the sweet pepper fresh yield obtained from the model and the measured dry yield, the simulated values were multiplied by moisture content coefficient of 15% established according to Vengaiah and Pandey (2007). The RMSE has been calculated using:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=0}^{n}(Y_i - Y_0)^2} \qquad 1$$

Where n is the number of observations, and Y_i and Y_o are respectively the simulated and observed yields.

Table 3 and Figure 11 show the model evaluation results. The sweet pepper simulated yields do not show good agreement with the observed values with a low R^2 equal to 0.45, a negative correlation and the RMSE of 437 kg/ha. That disagreement between simulated and observed sweet pepper yield may be due to plant diseases and pests effects that are not taken in account in the model or the quality of the measured yield data.

Based on the mean bias, one can conclude that the model underestimates the yield for all the four crops (Table 3). The highest bias is observed with potato grown at Bonkoukou. Due to the limited data used for that tentative evaluation of the models, we would suggest further data collection is in order to perform a complete calibration and validation of the models on those areas and crops, as well as for the simulation of crop yield and soil water balance parameter.

Table 3: DSSAT models evaluation results.

Location	**Crop**	**Years**	**Simulated fresh yield**	**Simulated dry yield**	**Observed Yield**	**Bias**	**RMSE**	**R^2**
			(Kg/ha)					
Diffa	Sweet pepper	1999	8249	1237	1054	183.4	437	0.45
		2000	7969	1195	1096	99.4		
		2001	7491	1124	1933	-809.4		
		2002	7382	1107	1310	-202.7		
		2003	7651	1148	1649	-501.4		
		2004	7417	1113	1506	-393.5		
		Average	7693	1154	1425	-271		
Niamey	Cabbage	2005	10150					
		2006	9181					
		Average	9666		12100	-2435		
Bonkoukou	Potato	2005	5970					
		2006	12287					
		Average	9129		13199	-4071		
Keita	Tomato	2005	5565					
		2006	8663					
		Average	7114		7522	-408		

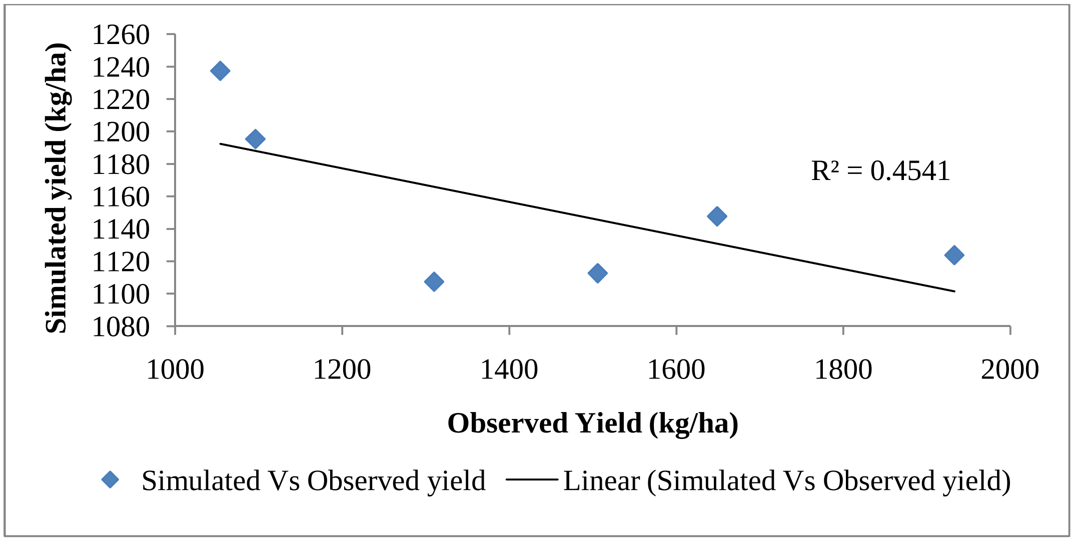


Figure 11: Observed yield against simulated yield for sweet pepper at Diffa.

- ***CROPWAT evaluation***

Due to the lack of field measurements on crop evapotranspiration, Kc, and the soil water balance parameters, the performance of the models in simulating those parameters has not been assessed. However, the use of CROPWAT for similar previous research has led to satisfactory results (Kuo et al., 2006, Raja, 2010).

3.5.2. Methods of estimation of crop irrigation water requirements using CROPWAT

The daily reference evapotranspiration (ET_o) values were calculated for Galmi, Keita, Niamey, Bonkoukou, and Diffa based on the sequence of historical weather data available for each site, using the FAO Penman-Monteith method. According to several studies (Dehghanisanij et al., 2004; and Kashyap et al., 2001), that method will give reasonable ET_o data for semi-arid zones. The relationship is (FAO 56):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

where, ET_o is the reference evapotranspiration [mm day^{-1}], R_n is the net radiation at the crop surface [MJm^{-2} day^{-1}], G is the soil heat flux density [MJ m^{-2} day^{-1}], T is the mean daily air temperature at 2 m height [°C], u_2 is the wind speed at 2 m height [m s^{-1}], e_s is the saturation vapor pressure [kPa], e_a is the actual vapor pressure [kPa], Δ is the slope vapor pressure curve [kPa °C^{-1}], and γ is the psychrometric constant [kPa °C^{-1}].

The crop coefficient (Kc) values for the five crops at the different growth stages have been determined using FAO Kc estimation methods found in the FAO Irrigation and Drainage Paper Number 56. The default values of crop coefficient were adjusted to the locations climatic conditions as recommended for initial and midseason stages. However, the default Kc values at the late season stage (Kc end) have been used without adjustment.

The calculated ET_o, the crop and soil data embedded to the CROPWAT model adapted to the locations characteristics, and the observed rainfall data, were used to simulate the crop irrigation requirements. The ET_o and the Kc values were used to estimate the crop reference evapotranspiration (ET_c). Three planting dates were chosen within the planting period suggested by the FAO crop calendar for each of the study areas. Those dates were selected at the beginning (early planting date), middle (average planting date), and ending (late planting date) of that period. The irrigation water requirement for each of the crops and planting dates is the difference between the crop ET_c and the effective rainfall.

The crop files, the climate parameters and ET_o files, and the FAO default soil files were hence used as input data in the CROPWAT program to simulate the irrigation water requirements for each of the crops relatively to the selected study areas. The simulations were run for each annual cropping season according to the three planting scenarios. The simulations outputs were statistically analyzed to determine the average crop water needs for each ten-day period throughout the crop cycle. An F-test statistic (one-way ANOVA) was used to analyze the inter-annual variability of the irrigation water required per dekad along the whole cropping cycle.

3.5.3. Methods to assess the climate change impacts

- ***Simulation of predicted yield, season length and irrigation requirements using DSSAT***

The historical and predicted irrigation requirements, growing season length, and yield for potato, cabbage, tomato, and sweet pepper have been simulated using DSSAT. The simulations input files for DSSAT were built first. They include the weather files and the experiment files containing the soil and crop information. The weather files were created by importation of the historical and the predicted climate datasets. The default crop information in the model was used with different planting dates according to the FAO suggested crop calendar and the farmers' practice reported in the literature. The aim of using several planting dates was to investigate the optimum planting window leading to the maximum yield. For potato, cabbage, and tomato, 15 planting dates were selected from September 20th to November 30th. For sweet pepper 12 planting dates from the 10th of August to November 30th were used. An attempt was made to create new soil profiles with the soil information collected from the FAO Harmonized World Soil Database (HWSD). However, there was a high and abnormal inter-annual variability in the simulation outputs obtained with those profiles. Therefore, the default sandy loam soil profile available in the DSSAT models system was used to perform all the simulations. The irrigation options were set to maintain the soil available water above the depletion threshold in the management depth for each crop according to the recommendation in FAO 56. The irrigation efficiency was set to be 75%, and N fertilizer level was assumed to be non-limiting. The detailed information on the crop and soil input files are in Appendices A. Note that sweet pepper is started from transplanted seedlings.

For each of the crops and planting scenarios, three sets of simulations were run for 1981-2010, 2041-2070, and 2071-2100 periods corresponding to the historical, mid-century, and end-century timelines respectively.

- ***Simulation of predicted irrigation requirements by CROPWAT***

The historical and predicted irrigation water needs were estimated using the CROPWAT model and the predicted weather data. The results from the previous section of the present study showed that the early planting dates require less irrigation water requirements estimation using that model. Therefore, simulations were run based on one optimum planting date for each of the crops.

- ***Description of methods used to analyze simulations outputs***

The average seasonal irrigation water requirements, the mean yield, and season length for the mid-century and end-century were compared separately to the historical values by computing the percentage of change between each of the two periods with the historical period. The change in the irrigation requirements and in the average yield has been calculated using:

$$\Delta IR = \frac{IR - IR_h}{IR_h} \times 100 \qquad 3$$

$$\Delta Y = \frac{Y - Y_h}{Y_h} \times 100 \qquad 4$$

where, ΔIR is the variation of the irrigation requirement, IR is the average irrigation requirement at mid-century (or end-century), IR_h is the current average irrigation requirement, ΔY is the variation of the crop yield, Y is the average yield at mid-century (or end-century), and Y_h is the current average yield.

CHAPTER IV

RESULTS AND DISCUSSION

4.1. Crop irrigation water requirements using historical data with CROPWAT

Table 4 shows the Kc values for the five crops according to the three planting dates chosen for each site. The highest Kc values were found for mid-season, corresponding to the reproductive stage. Those results imply that the largest water consumption is expected to occur during that stage.

Table 4: Planting periods and corresponding crop coefficients.

Sites	Crops	Planting periods	Planting dates	Kc values		
				Kc ini	Kc mid	Kc end
Bonkoukou	Potato	Early planting (P1)	10/01	0.69	1.20	0.75
		Mid-season planting (P 2)	11/01	0.67	1.21	0.75
		Late planting (P 3)	12/01	0.69	1.25	0.75
Keita	Tomato	Early planting (P1)	10/01	0.65	1.15	0.90
		Mid-season planting (P 2)	12/01	0.67	1.15	0.90
		Late planting (P 3)	01/21	0.62	1.15	0.90
Galmi	Onion	Early planting (P1)	10/01	0.80	1.03	1.00
		Mid-season planting (P 2)	12/11	0.80	1.03	1.00
		Late planting (P 3)	02/21	0.70	1.00	1.00
Diffa	Sweet pepper	Early planting (P1)	09/01	0.75	1.05	0.90
		Mid-season planting (P 2)	11/11	0.85	1.30	0.90
		Late planting (P 3)	01/21	0.70	1.05	0.90
Niamey	Cabbage	Early planting (P1)	10/01	0.70	1.05	0.95
		Mid-season planting (P 2)	11/11	0.68	1.05	1.05
		Late planting (P 3)	12/21	0.68	1.05	0.95

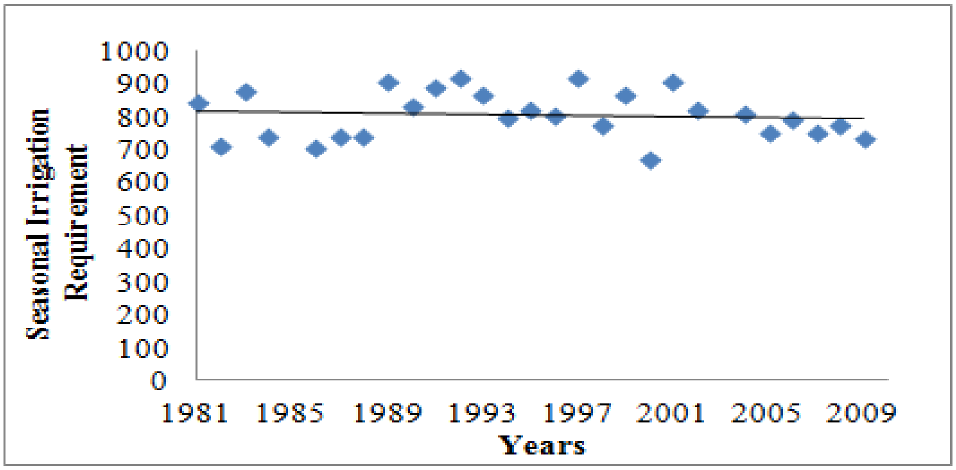
4.1.1. Irrigation water requirements for Potato at Bonkoukou

The years 1985 and 2003 were eliminated due to the large amount of missing values in the weather data file. The overall growing season length was set at 130 days following the crop calendar generated by the FAO Agriculture Production and Protection Division (FAO, 2010). Therefore, the cycle was divided in 13 dekads (10-day periods). The whole cycle irrigation water requirements were on average 803, 871, and 975 mm for the early, the mid-season and the late planting dates respectively (Appendix C1). The first two planting scenarios resulted in irrigation requirements showing agreement with Vanderhofstadt and Jouan (2009) who recommended 5000 to 8000 m^3/ha as potato crop water needs per season. Figure 12 shows a relatively constant trend of the total irrigation water requirements throughout the years for each of the planting scenarios.

The results of the F-test statistics run for each dekad over the 28-year period are listed in Appendix D1. The minimum, maximum, and average dekadal irrigation water requirements are given in Appendix B1. The ANOVA tables in Appendix D1 show that during the first dekads of the growing cycle (corresponding to the initial and development stages), there is no significant difference between the mean water needs as function of the planting date. Therefore, 40mm, 41mm, 45mm, 54mm, and 66mm listed in Table 5 can be recommended as potato irrigation water requirements at Bonkoukou for the first five dekads of the growing season.

Concerning the mid-season and late season stages, the average values from dekads 6 through dekads 13 are respectively 81, 80, 83, 84, 89, 83, 76, 58 mm. The F-test statistic reveals a significant difference between the means irrigation water requirements relative to the planting dates. During those stages, the deviation from the mean values that appears in Figure 13 illustrates that the dekadal irrigation water requirement is variable from a year to another for the same planting date. Based on those results, the average values could not be suggested as the potato water requirements for the mentioned periods. However, they can be used as the basis for further investigation and field experimentation in order to determine the adequate water requirements at those stages. Figure 14 shows that the early planting requires less water during the mid-season and late season stages.

Considering the overall growing season (Figure 15), it appears that the earlier the planting date, the lower the irrigation water needs. That may be explained by the coincidence of the end of the rainy season with the beginning of the potato growing season, and the lower reference ET at the end of the cycle of the early planted crop. Hence, the early planting period would be a good strategy in terms of irrigation management for potato growth.



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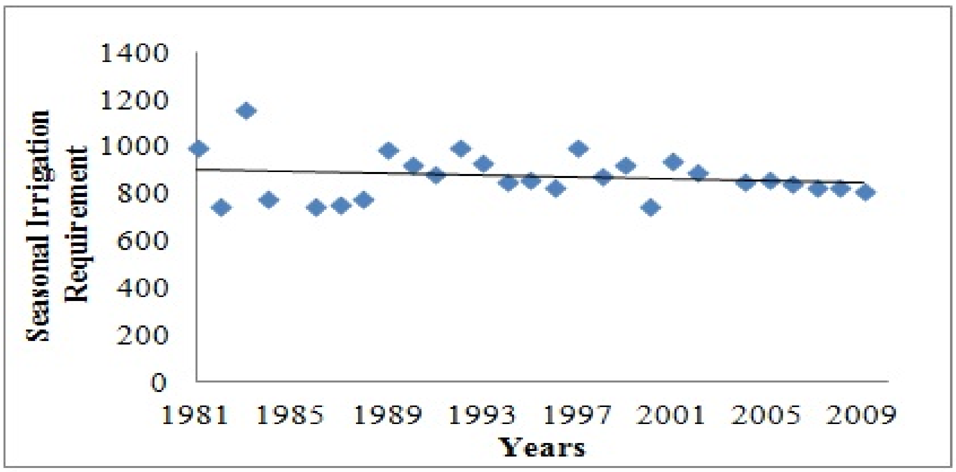

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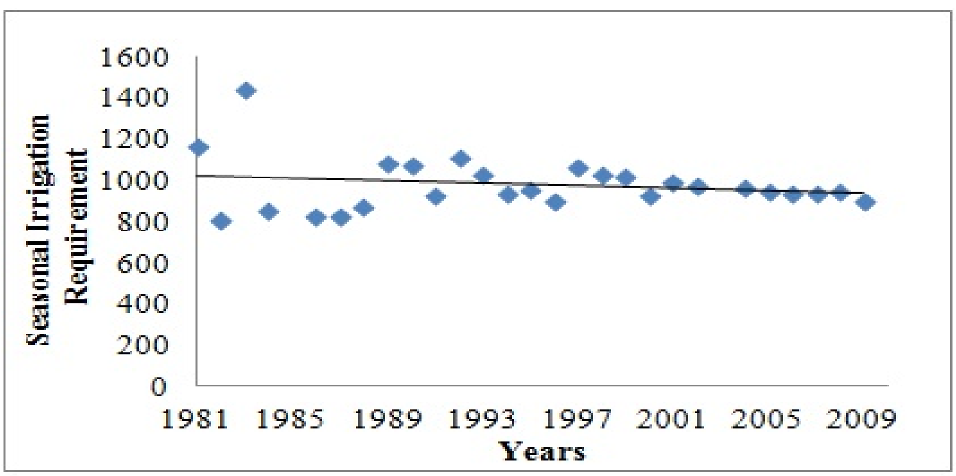
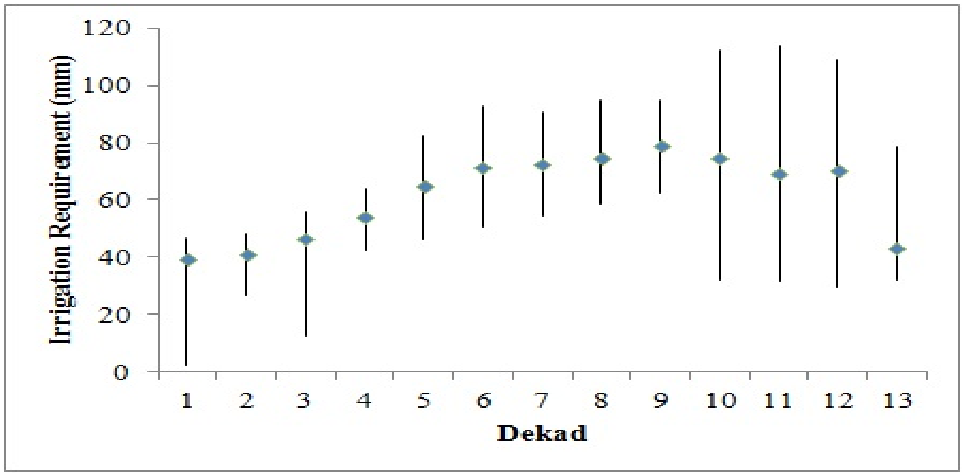


(c)

Figure 12: Seasonal potato irrigation water requirements at Bonkoukou over the years for: (a) October 1st planting, (b) November 1st planting, (c) December 1st planting.



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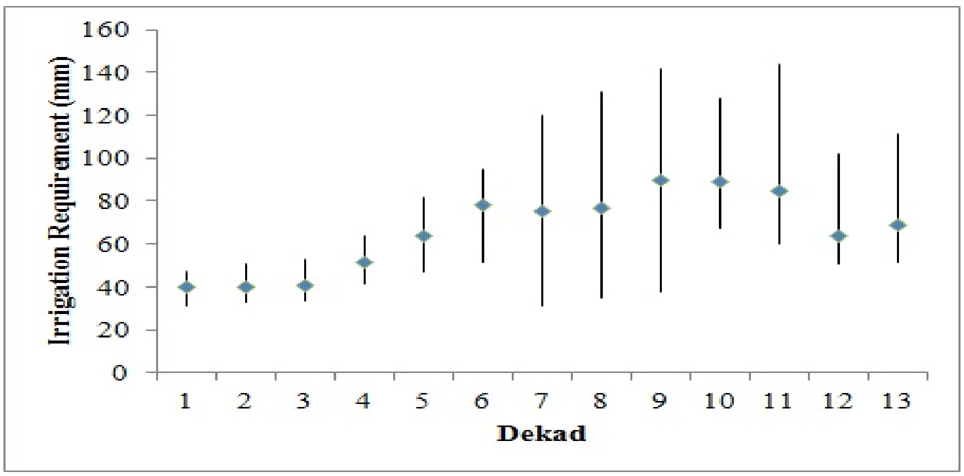

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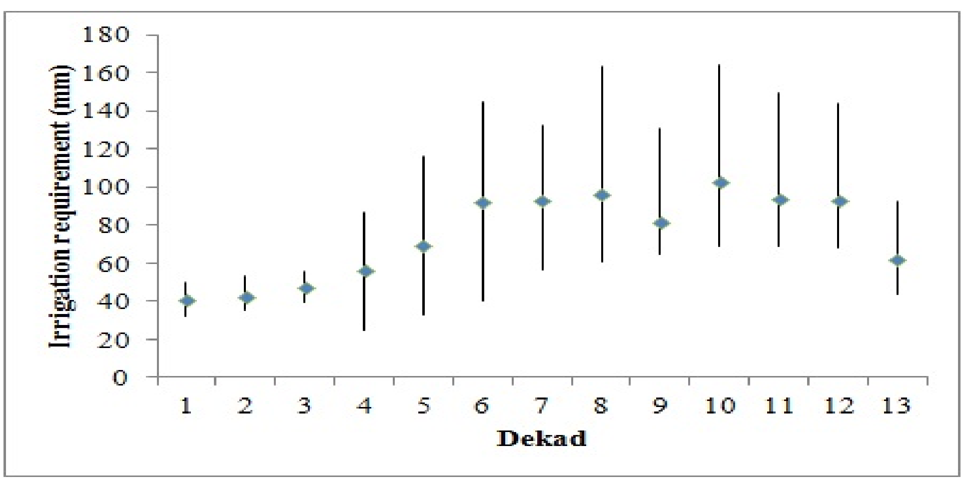


(c)

Figure 13: Maximum, minimum, and average dekadal potato irrigation requirements at Bonkoukou: (a) October 1st planting, (b) November 1st planting, (c) December 1st planting.

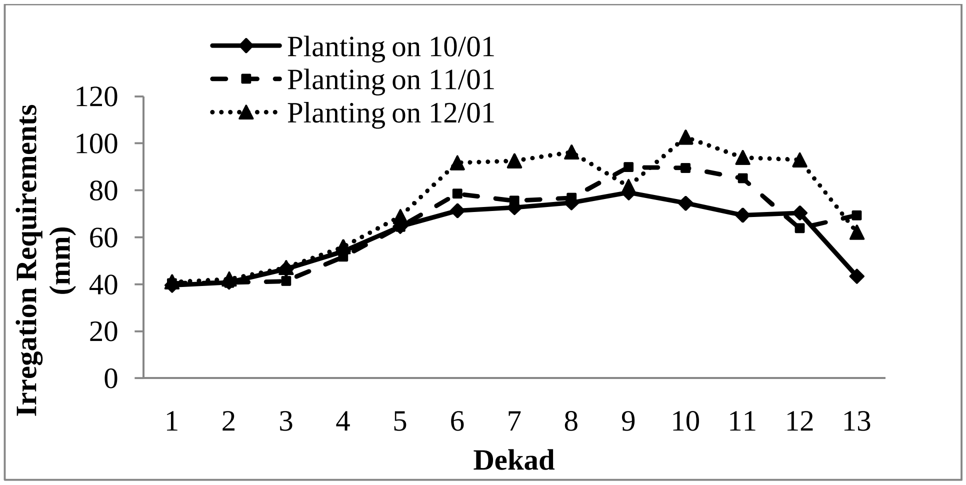


Figure 14: Comparison of the average dekadal potato irrigation requirements at Bonkoukou based on 3 different planting dates.

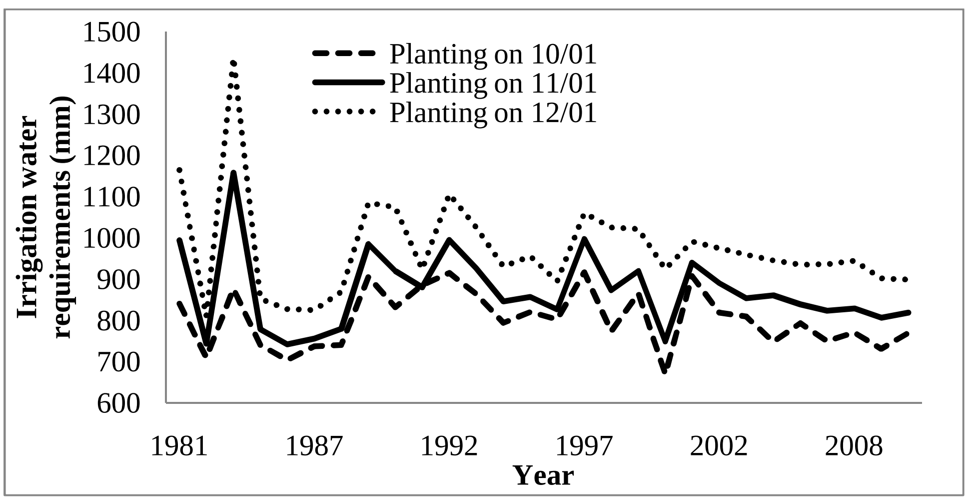
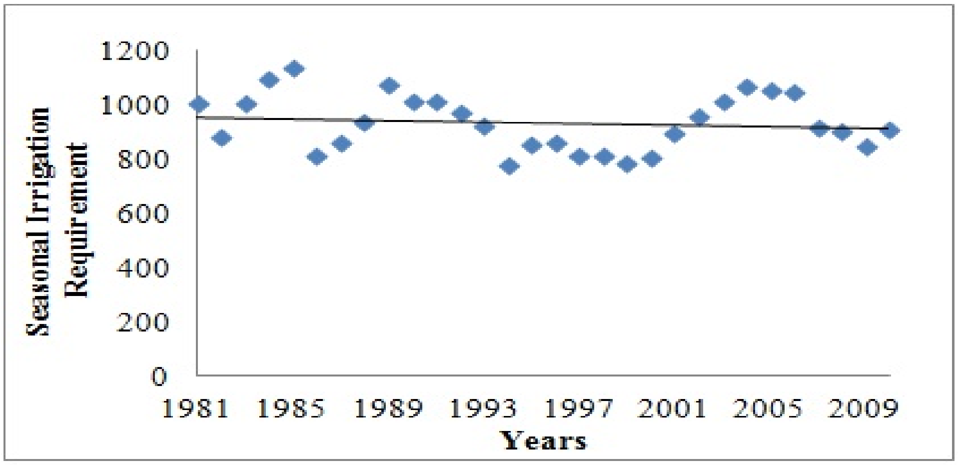


Figure 15: Comparison of potato seasonal irrigation requirement at Bonkoukou based on the 3 planting scenarios.

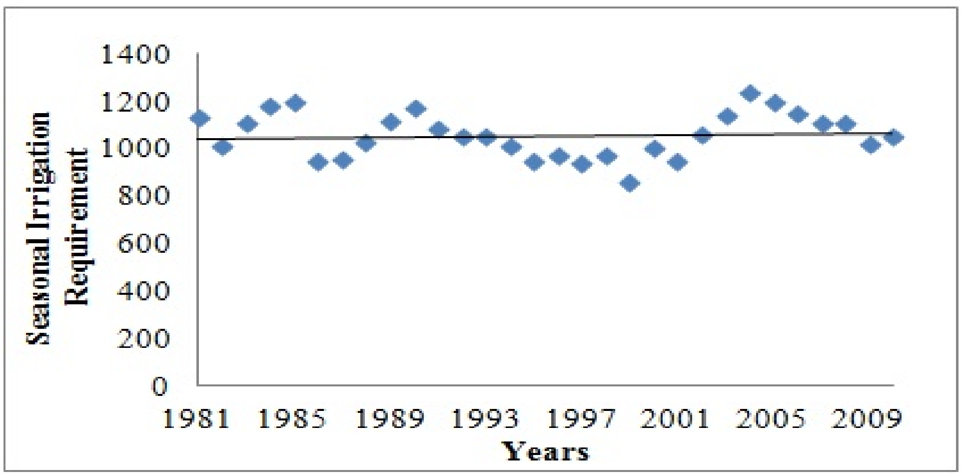
4.1.2. Irrigation water requirements for tomato at Keita

The F-test results are presented in Appendix D2. The average tomato growing season length in that location is 145 days. Appendix C2 presents the seasonal irrigation water needs per year. It appears to be constant throughout years (Figure 16). The average water needs for tomato are 930 mm, 1052 mm, and 1066 mm per growing season for planting on October 1st, December 1st, and January 21st respectively (Appendix C2).

Appendix B2 lists the minimum, maximum, and average irrigation water requirements for each of the 15 dekads of the growing season and for each planting scenario. Except for dekads 2, 3, and 14, the F-test statistic resulted in a difference between the mean dekadal water requirements as function of the planting date. However, the magnitude of that difference seems to be small (Figure 17). Therefore, the dekadal water requirements for tomato grown at Keita would be the overall average value listed in the last column of Appendix B2. The higher irrigation water requirements occur from dekads 8 through 14 corresponding to the tomato reproductive stage when it is 9 mm/day (or 90 m3/ha/day) on average. The early planting scenario requires less irrigation water than the other planting periods during that stage (Figure 18). Figure 19 also shows that the seasonal irrigation requirement is lower for the early planting; therefore starting the tomato cropping around the first of October at Keita would be a best strategy in terms of irrigation water management.



(a)



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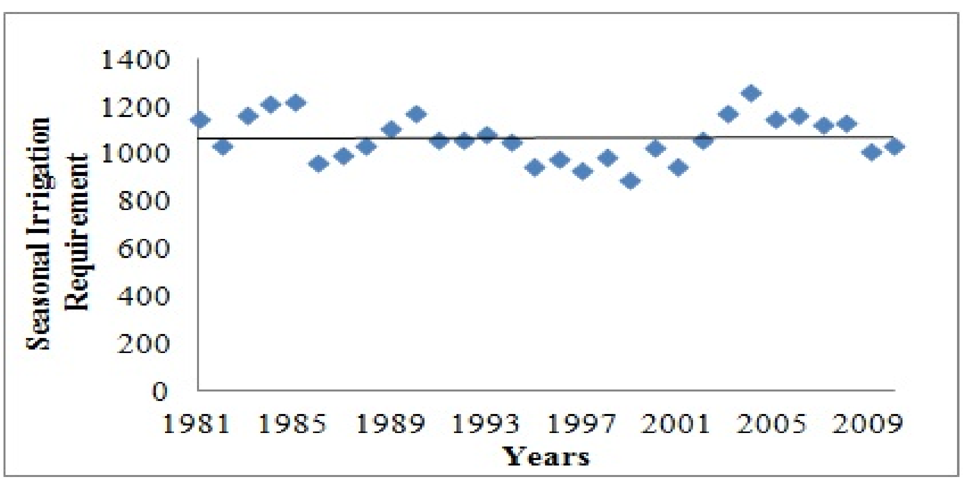
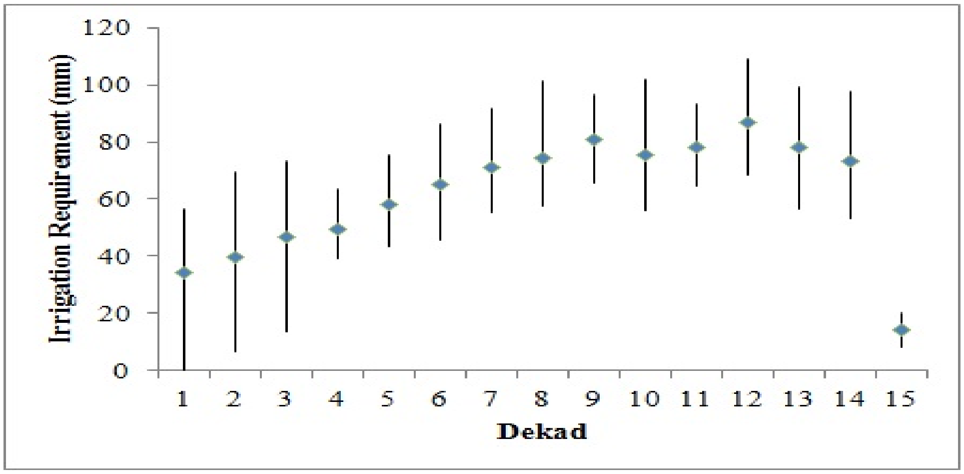
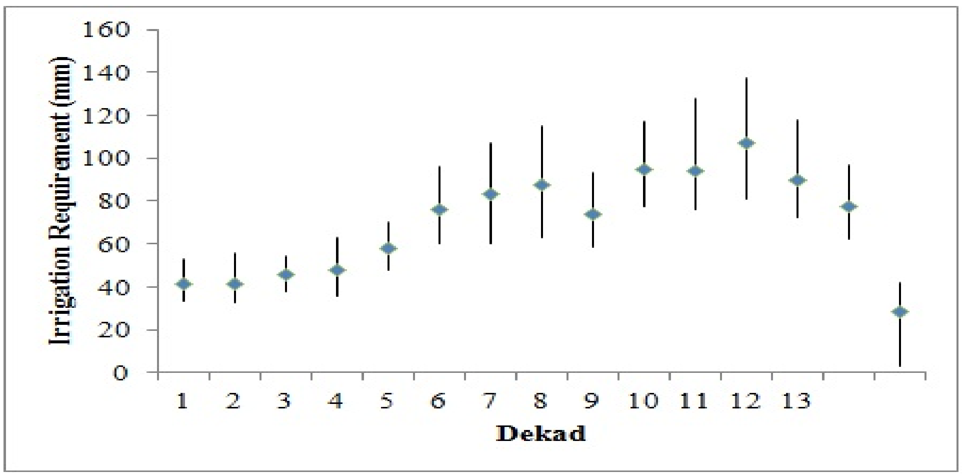


(c)

Figure 16: Tomato seasonal irrigation water requirements at Keita over the years for: (a) October 1st planting, (b) December 1st planting, (c) January 21st planting.



(a)



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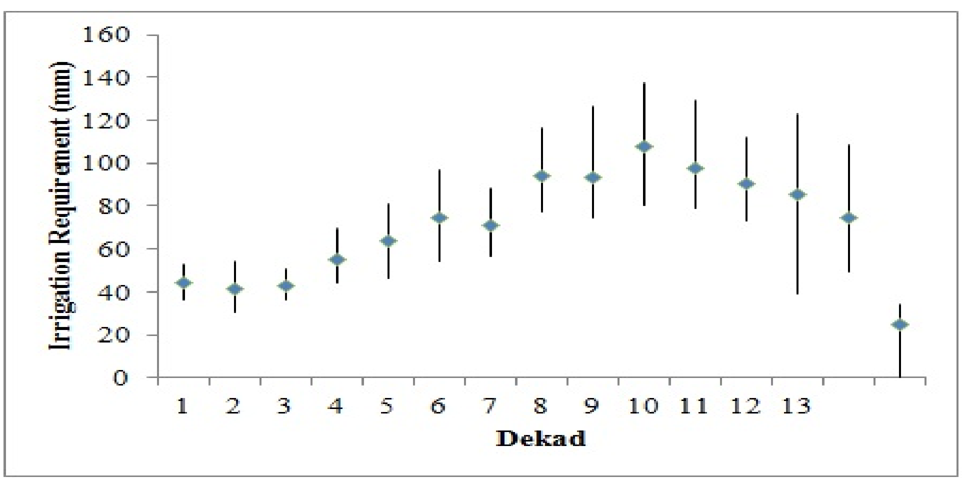


(c)

Figure 17: Maximum, minimum, and average dekadal irrigation requirements for tomato at Keita: (a) October 1st planting, (b) December 1st planting, (c) January 21st planting.

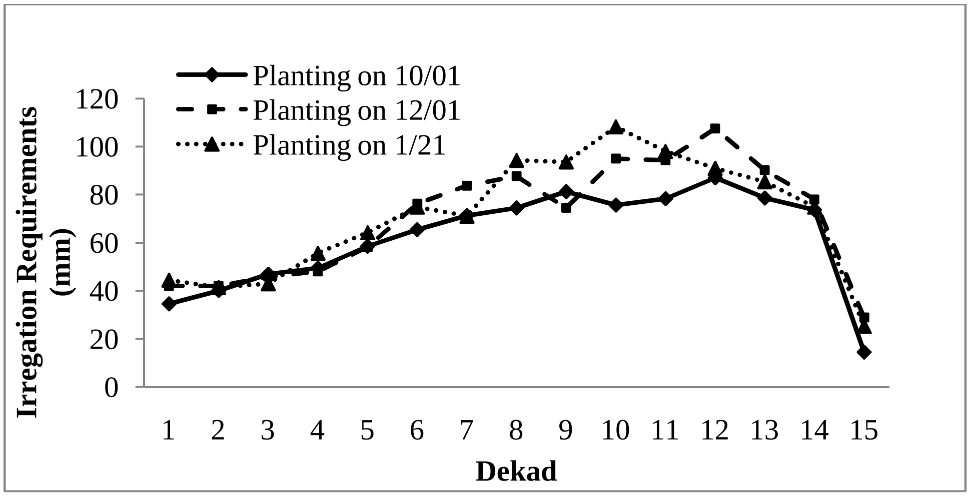


Figure 18: Comparison of tomato average dekadal irrigation requirements at Keita based on three different planting dates.

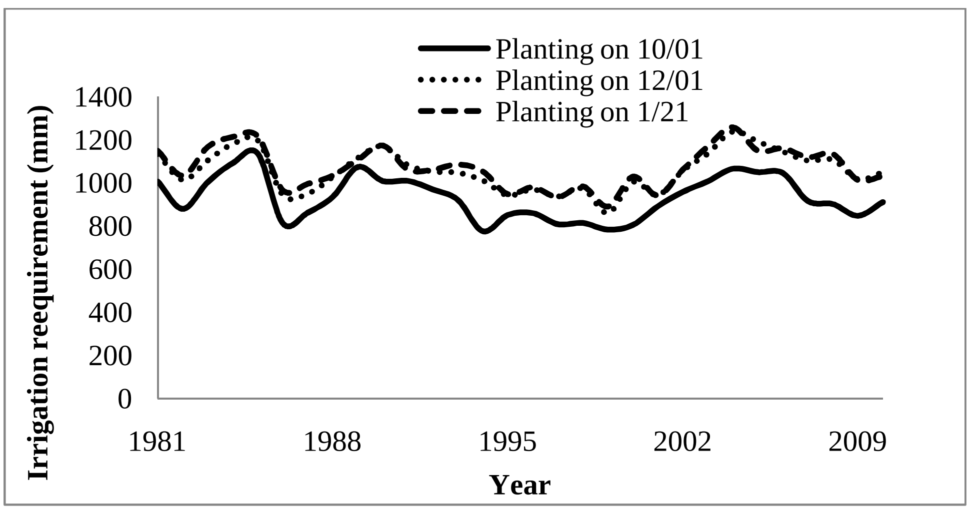
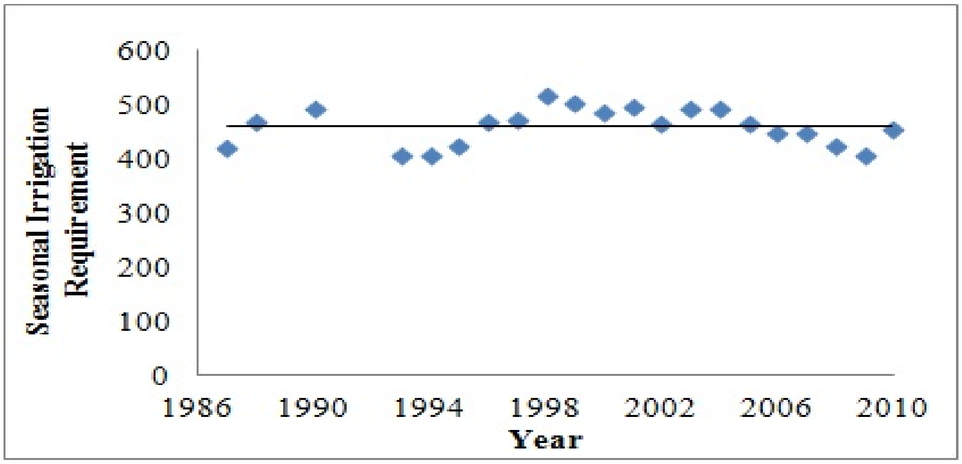


Figure 19: Comparison of the tomato seasonal irrigation requirement at Keita based on the three planting scenarios.

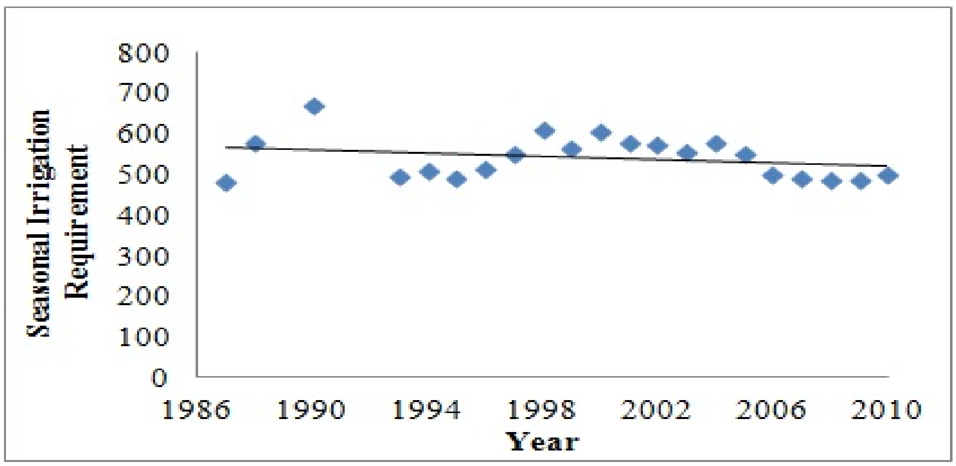
4.1.3 Irrigation water requirements for onion at Galmi

In practice, onion is cultivated year-round at Galmi. However, this study focused on the dry season onion growth. The average growing season length is 110 days or 11 dekads. Simulations were run from 1987 to 2010 except for 1987, 1992, 1993 which were removed from the sequence due to insufficient weather data. The F-test results are in Appendix D5. The mean irrigation water requirements per growing season for onion (Appendix C5) were 459 mm, 541, and 546 for planting on the first of October, 11th of November, and 21st of February respectively. Figure 20 show that there is no significant variability of the onion irrigation water requirements throughout the years for a planting around the first of October and a slight decreasing trend in the cases of the two other planting dates.

The F-test showed a difference between the average irrigation water requirements per dekad as function of a change in the planting date. A deviation of the minimum and maximum from the mean value is observed for the late planting scenario (Figure 21). However, that difference seems to be negligible (Figure 22). Based on those results, the water requirements per dekad for dry season onion at Galmi would be the overall average values listed in the last column of Appendix B5. Figure 23 show mid-season and late season planting scenarios lead to similar water requirements whereas the early planting scenario requires lower irrigation water. As for the crops discussed previously, starting onion growth around the first of October at Galmi would reduce the irrigation management.



(a)



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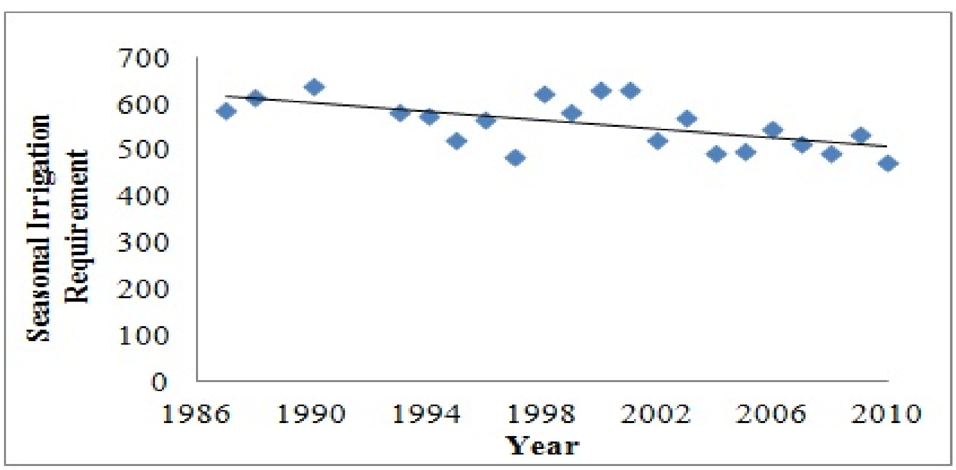
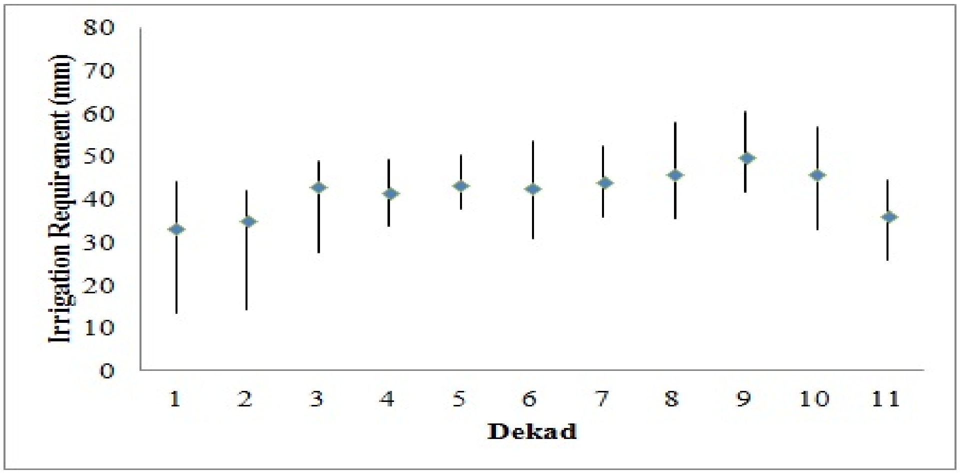
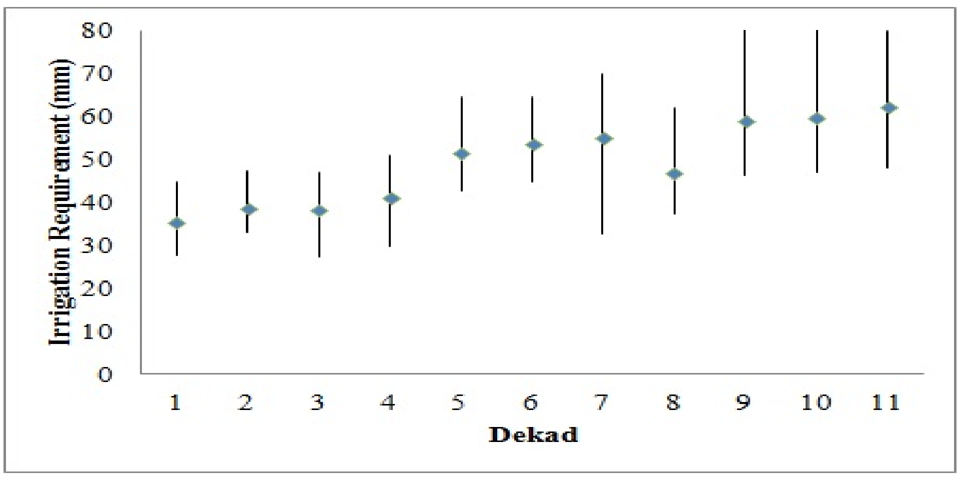


(c)

Figure 20: Comparison of the tomato seasonal irrigation requirement at Keita based on the three planting scenarios.



(a)



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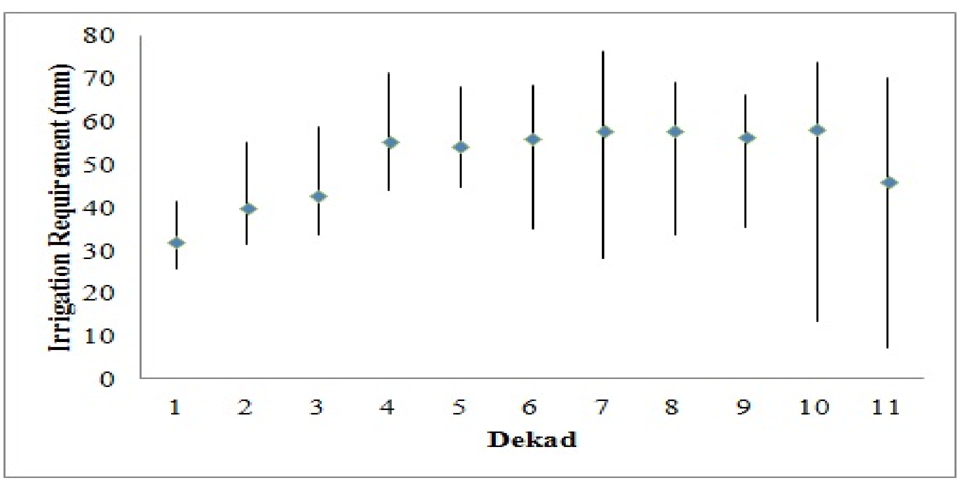


(c)

Figure 21: Maximum, minimum, and average dekadal irrigation requirements for onion at Galmi: (a) October 1st planting, (b) November 12th planting, (c) February 21st planting.

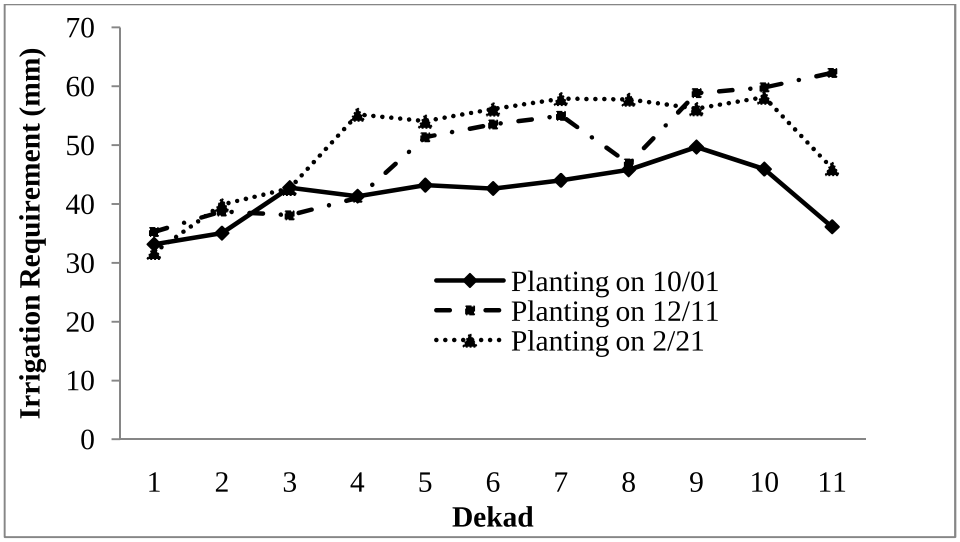


Figure 22: Comparison of onion average dekadal irrigation requirements at Galmi based on three different planting dates.

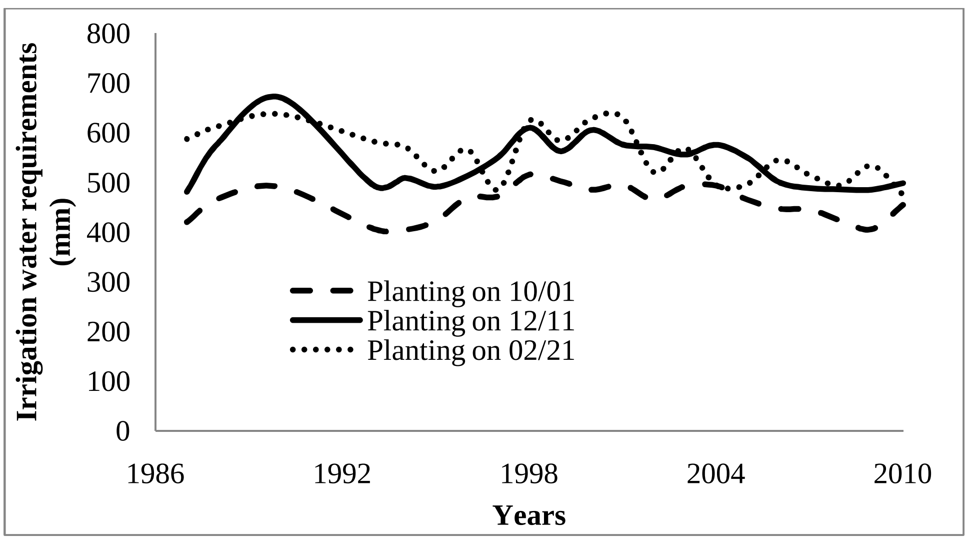
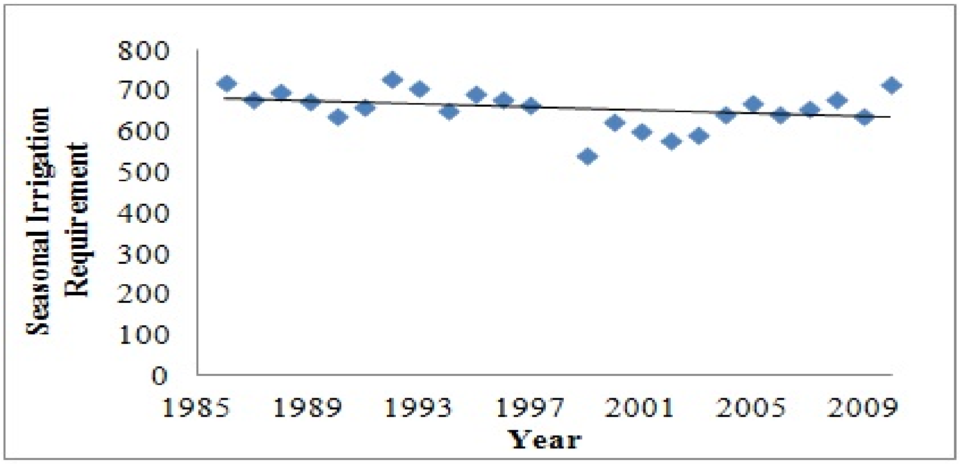


Figure 23: Comparison of the onion seasonal irrigation requirement at Galmi based on three planting scenarios.

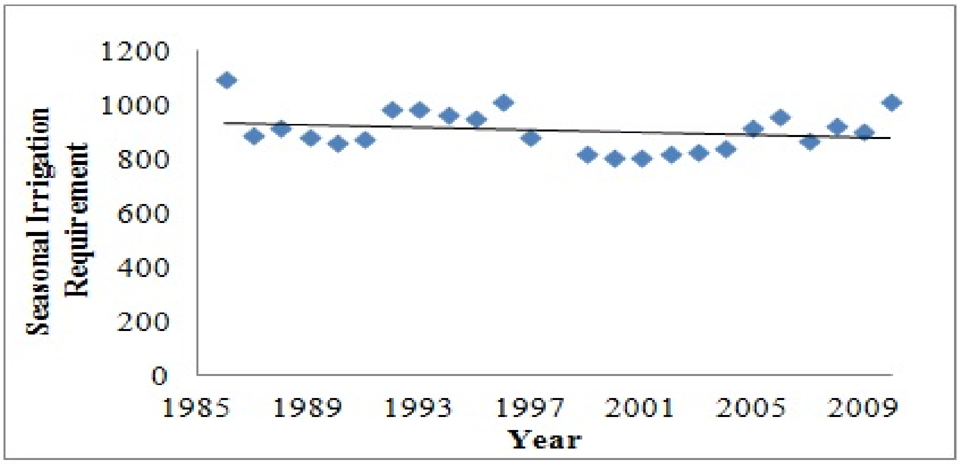
4.1.4. Irrigation water requirements for sweet pepper at Diffa

Simulations for sweet pepper irrigation water needs at the location of Diffa were carried out for 150 days or 15 dekads growing season and three different planting scenarios (Table 4). They were run from 1986 to 2010 excluding 1998 because of insufficient weather data for that year. Appendix D3 present the F-test results. Appendix C3 shows that the average water needs per growing season were 657, 906, and 874 mm according to the three planting scenarios, 1st of September, 11th of November, and 21st of January. For each planting scenario, the seasonal irrigation water needs remain relatively constant over the years (Figure 24).

The F-test revealed a significant difference between the mean dekadal irrigation water. Appendix B3 and Figure 25 show that the difference occurs at the initial stage for planting scenario one (1st of September), and at the end of the growing season for planting scenarios two and three (November and January). In the first case, that can be explained by the interannual irregular distribution of rainfall events at the end of the rainy season. In other terms, wet years with well distributed rainfall events over the period of September-early October will reduce the irrigation water needs of sweet pepper planted around the 1st of September, whereas in dry years (years when the rainy season stops earlier), more irrigation water is needed for the same planting date. In the cases of the two other planting scenarios, the large deviation from the mean occurring at the end of the growing season may be related to the high evapotranspiration at that time of the year. Figure 26 shows that the difference between the dekadal irrigation water requirements is higher at the mid-season and end season stages than at the beginning of the growing season. Based on those results, the sweet pepper irrigation water needs would be 34, 34, 37, 39, 51, 58, and 63 mm for the first seven dekads of the growing season, regardless of the choice of the planting dates. However, due to the high water consumption related to the last two planting scenarios (Figures 26 and 27), planting after the 10th of November should be avoided although the FAO global crop calendar extends the sweet pepper growing season onset until the end of January for that location. Therefore, the corresponding average values resulting from a planting on the 1st of September (Appendix B3) should be considered as the sweet pepper irrigation water needs from dekad eight to the end of the growing season.



(a)



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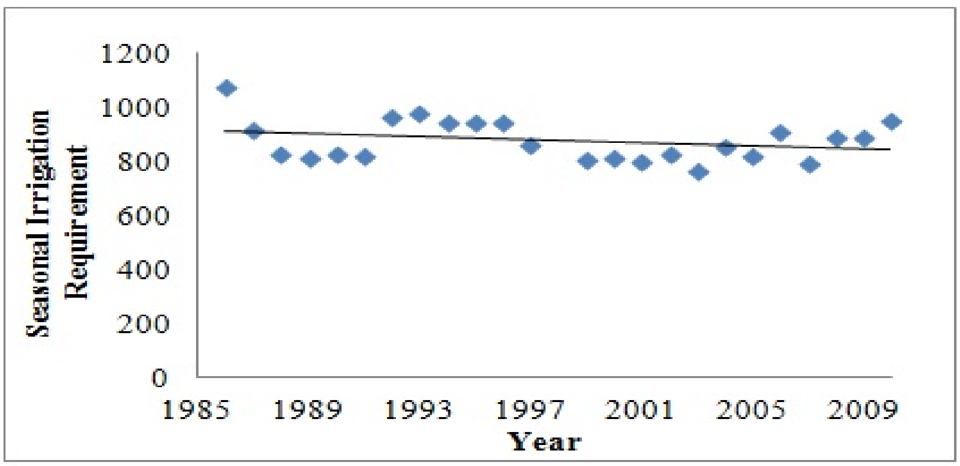
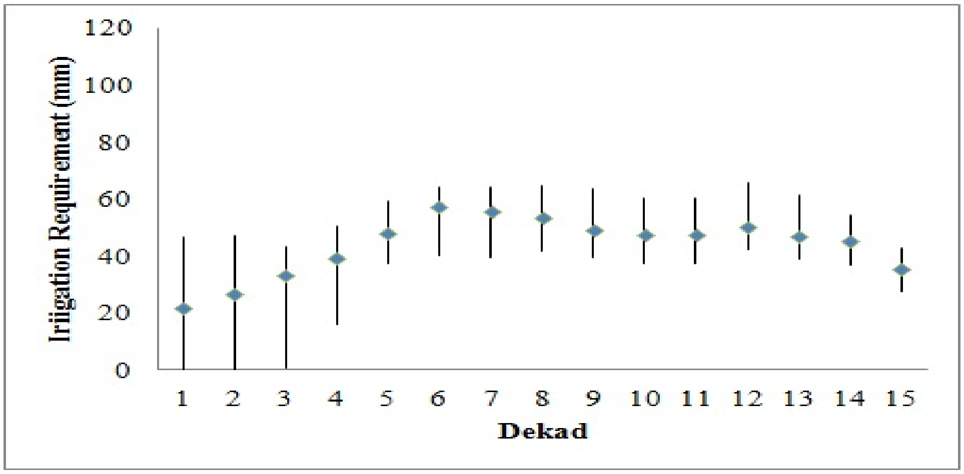
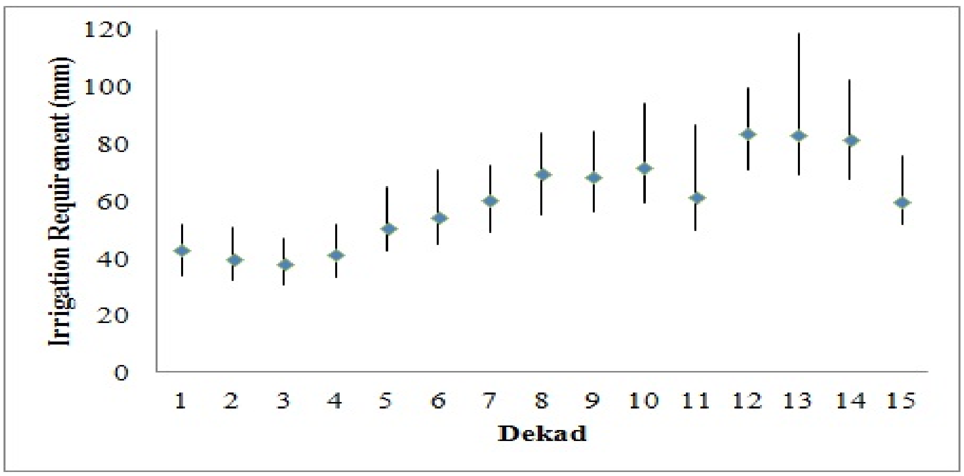


(c)

Figure 24: Inter-annual variability of sweet pepper seasonal irrigation water requirements at Diffa: (a) September 1st planting, (b) November 11th planting, (c) 21st of January planting.



(a)



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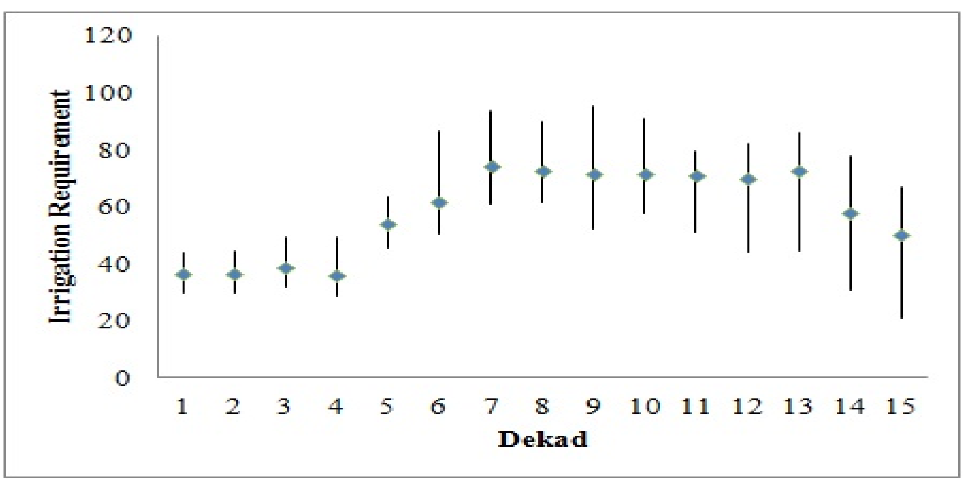


(c)

Figure 25: Maximum, minimum, and average dekadal irrigation requirements for sweet pepper at Diffa: (a) September 1st planting, (b) November 11th planting, (c) 21st of January planting.

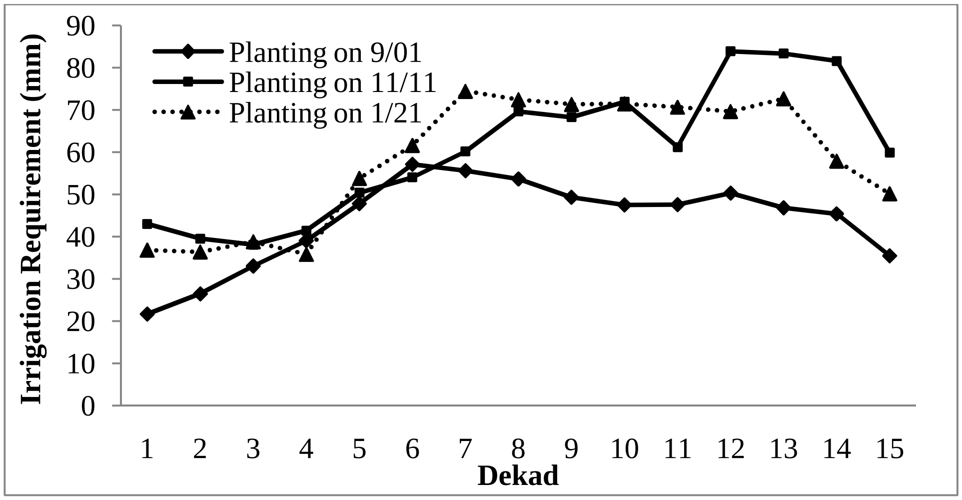


Figure 26: Comparison of sweet pepper average dekadal irrigation requirements at Diffa based on three different planting dates.

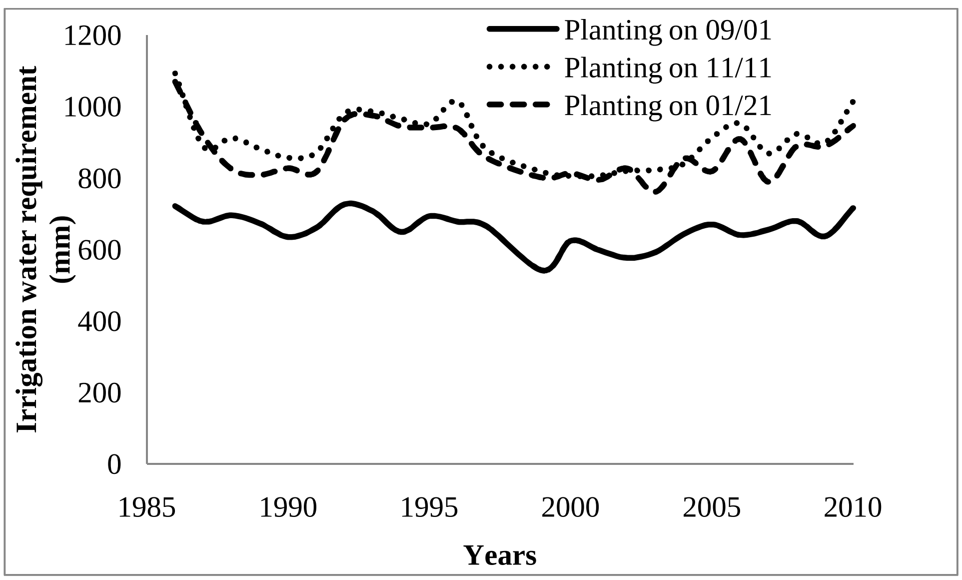


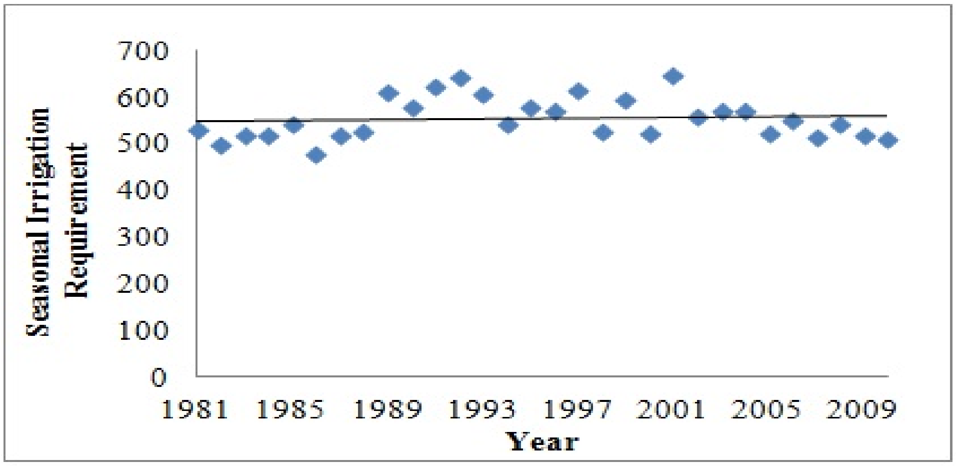
Figure 27: Comparison of sweet pepper seasonal irrigation requirement at Diffa based on three different planting dates.

4.1.5. Irrigation water requirements for cabbage at Niamey

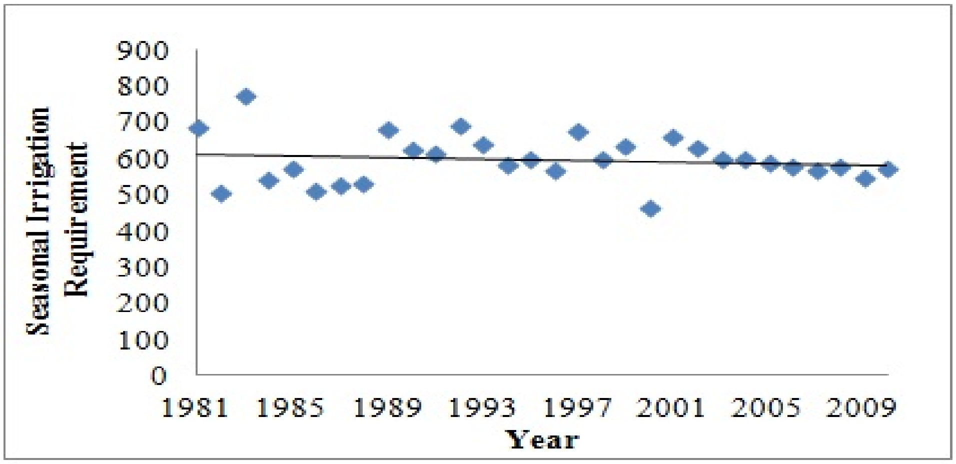
Irrigation water requirements for cabbage grown at Niamey were simulated for 30 years from 1981 to 2010 over a growing season of 100 days (10 dekads). The F-test results are listed in

Appendix D4. The average seasonal irrigation water requirements were 553, 596, and 713 mm for cabbage planted on the 1st of October, the 11th of November, and the 21st of December respectively (Appendix C4). Over the study period, the seasonal irrigation water requirement remains constant for the first two planting scenarios but shows a slight decreasing trend for the third planting scenario (Figure 28). The late planting date requires a little more irrigation water for the whole season compared to the other two planting dates having similar water needs (Figure31).

Except for dekad four, the F-test (Appendix D4) shows a difference between mean dekadal irrigation water requirements as function of the planting date. That difference is related to the large deviation from the mean values recorded from the mid-season to the late season growth stages in case of the planting scenario two (Figure 29b); and during all the growing season in case of the planting scenario three (Figure 29c). That may be explained by the high variability in wind and sunshine duration during the period of January through March, which influence the ETo. However, Figure 30 shows that the difference between mean dekadal water requirements may be neglected. Therefore, the overall average listed in Appendix B4 would be the dekadal irrigation water requirement for cabbage grown at Niamey.



(a)



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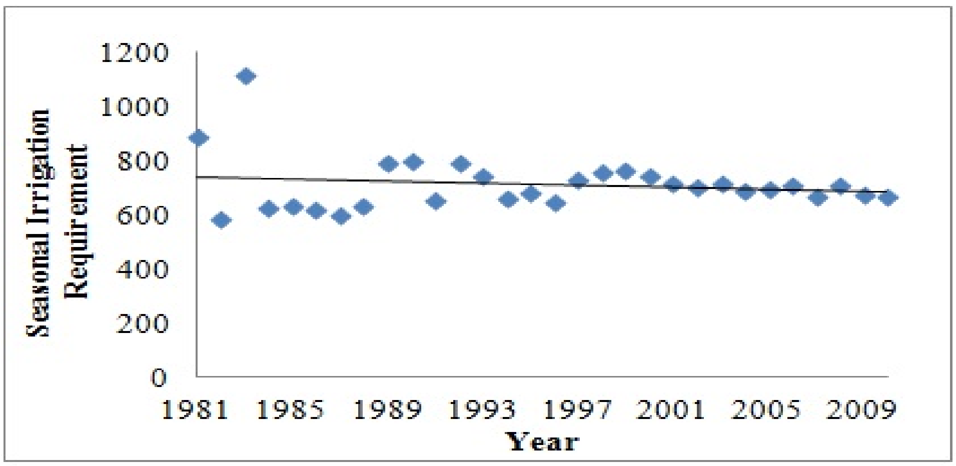
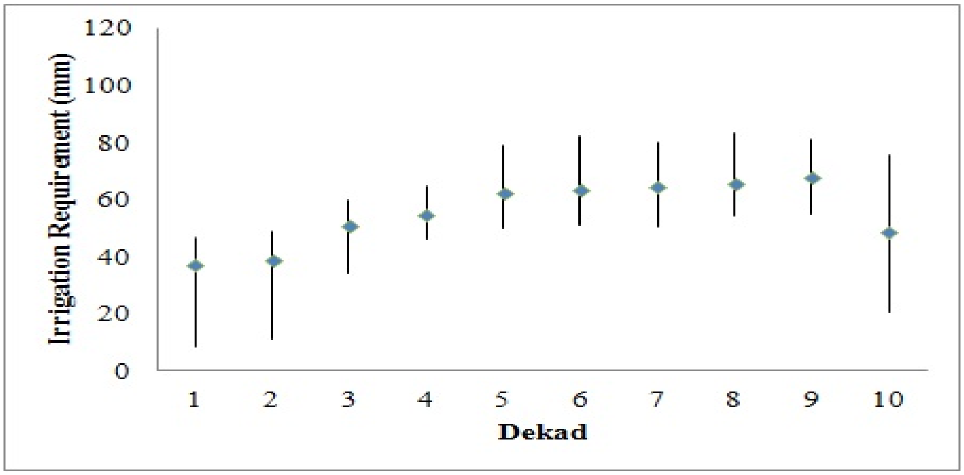
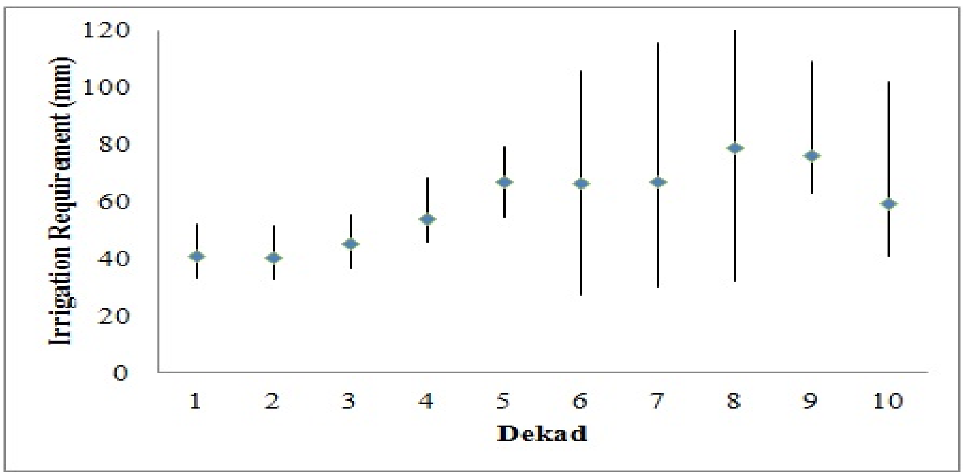


(c)

Figure 28: Inter-annual variability of cabbage seasonal irrigation water requirements: (a) October 1st planting, (b) November 11th planting, (c) December 21st planting.



(a)



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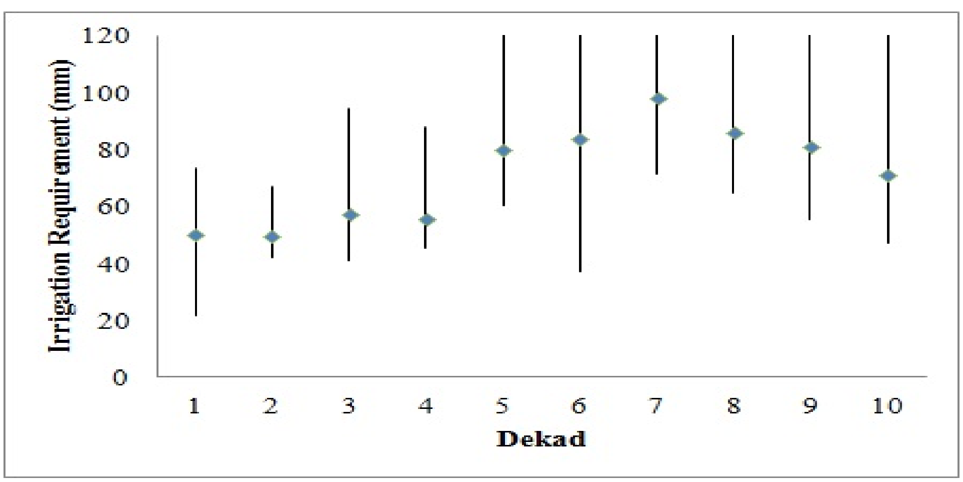

(c)

Figure 29: Maximum, minimum, and average dekadal irrigation requirements for cabbage at Niamey: (a) October 1st planting, (b) November 11th planting, (c) December 21st planting.

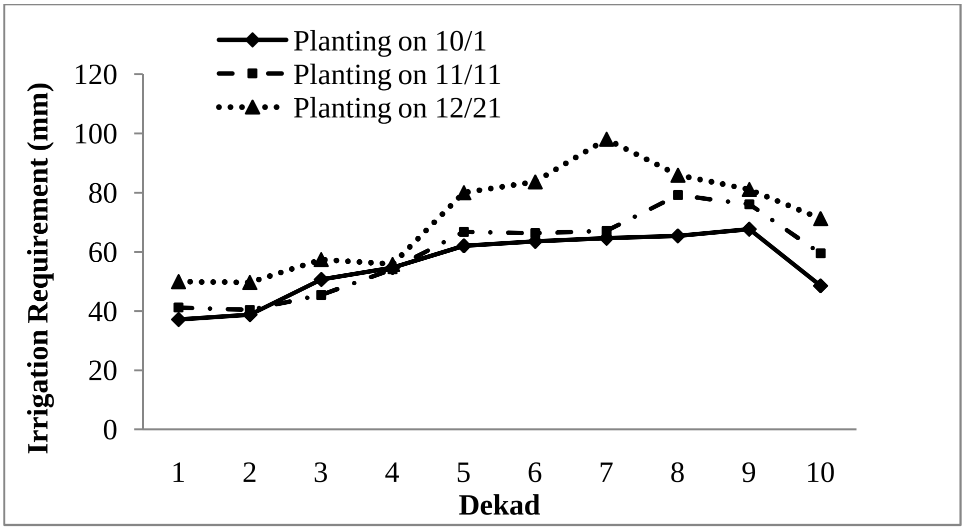

Figure 30: Comparison of the cabbage average dekadal irrigation requirements based on three different planting dates for cabbage grown at Niamey.

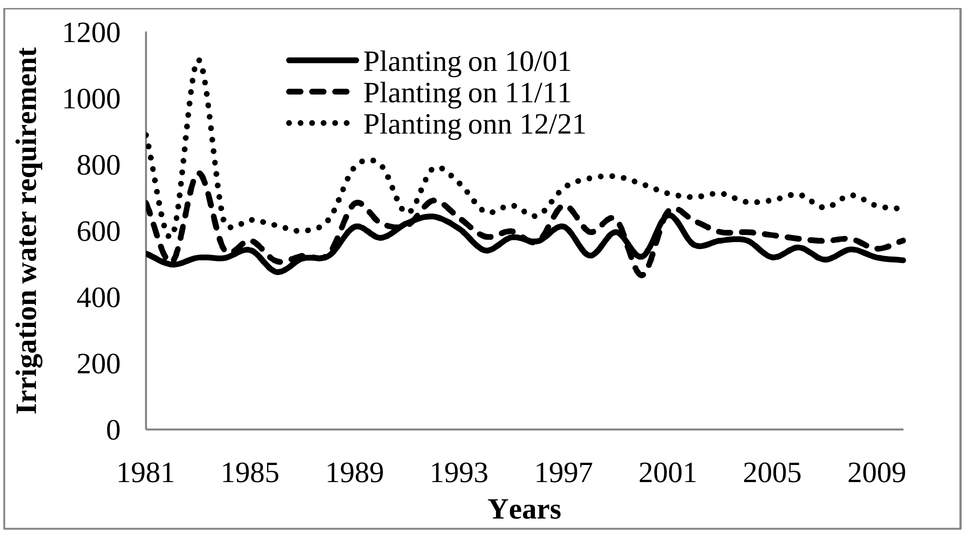

Figure 31: Comparison of the cabbage seasonal irrigation requirement based on three different planting dates for cabbage grown at Niamey.

4.1.6. Discussion

The early planting date scenarios resulted in lower irrigation water requirements, and can be used as the recommended growing season start dates for the different crops. Based on the early planting scenario and the crops cycle length, the daily crop irrigation water requirements estimates were 6.17 and 6.41 mm/day for potato and tomato grown at Bonkoukou and Keita respectively. For onion and sweet pepper grown at Galmi and Diffa, the crop irrigation water needs are estimated to be 4.71 and 4.38 mm/day respectively. The average irrigation water needs for cabbage at Niamey is 6 mm/day. Therefore, by assuming an irrigation efficiency of 75 %, the gross irrigation water needs will be 8 mm /day for potato, tomato, and cabbage; and 6 mm/day for onion and sweet pepper. These irrigation rates are assumed to be sufficient not only for crop production but also to prevent eventual salinization of the soil. The validity of this assumption depends on local soil and water conditions. These results compare well with Woltering et al. (2010, unpublished data) who found 10 to 12 mm/day as irrigation water applied following farmers practice and suggested 8 mm/day as improved technology for vegetables grown in Niger based on the maximum local evapotranspiration rate. Since the CROPWAT model has not been validated for these sites, field experiments are necessary before generalizing those findings.

4.2. Irrigation water requirements using predicted climate data

4.2.1. Observed trends in climate variability and change around the study sites

- ***Variability of the rainfall***

Figures 32, 33, 34, 35, and 36 show the inter-annual variability of rainfall around the study locations over the period 1961-2010. The discontinuities displayed in the plots for Keita, Galmi, and Bonkoukou are related to the missing data over the period 1961-1980.

In order to bring out the disparities hidden in the overall trend of the rainfall variability, five-year moving averages of the annual rainfall have been plotted over the same period 1961-2010 (Figure 37). For all the locations, there was a negative trend until the early 1980's, followed by an increasing trend until 2010. For Niamey in particular, the decreasing trend during the first part of the period was steeper than for the other sites despite the small increase from 1974-1977. That deep decrease mitigates also the mild increasing trend which has been observed since 1985, and may explain the overall negative trend over the whole period 1961-2010.

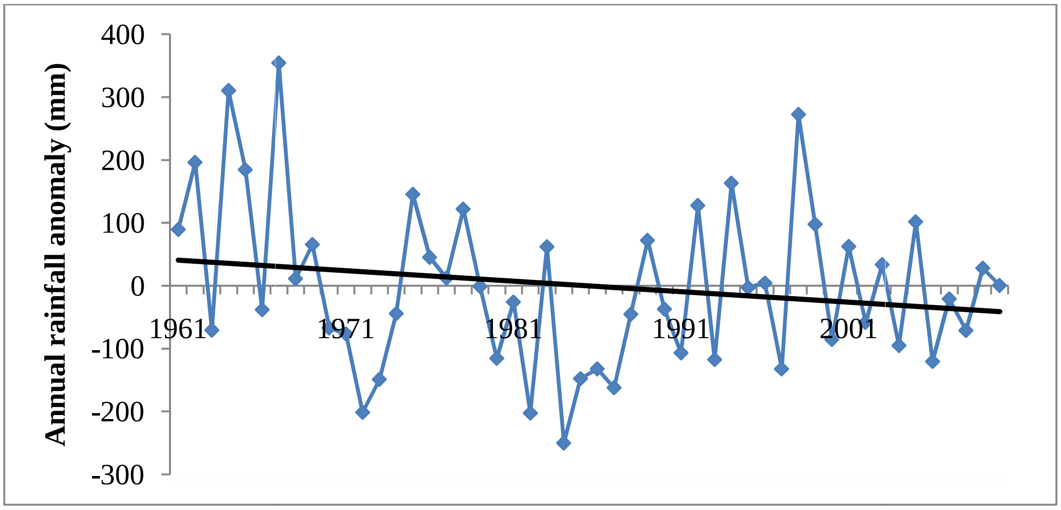

Figure 32: Inter-annual variability of the annual rainfall at Niamey.

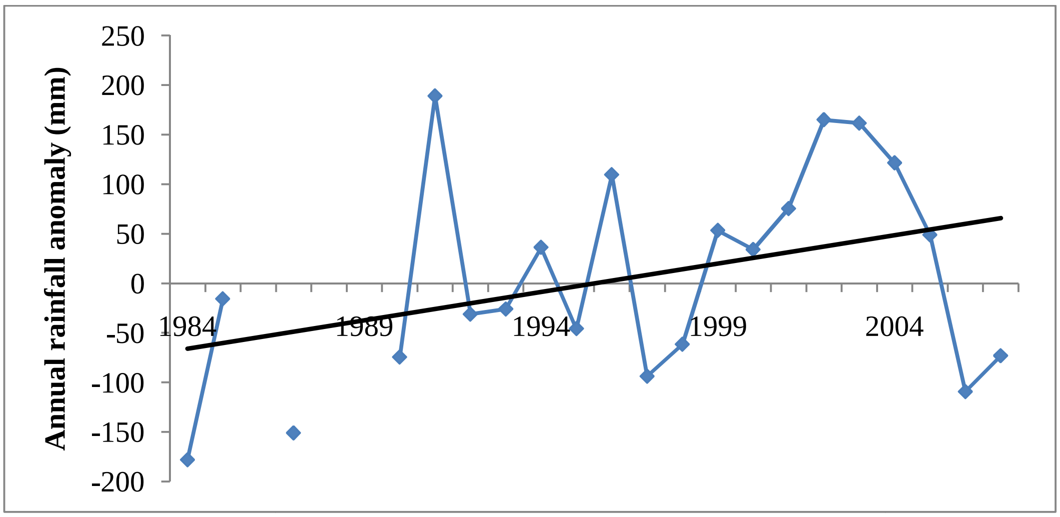

Figure 33: Inter-annual variability of the annual rainfall at Galmi.

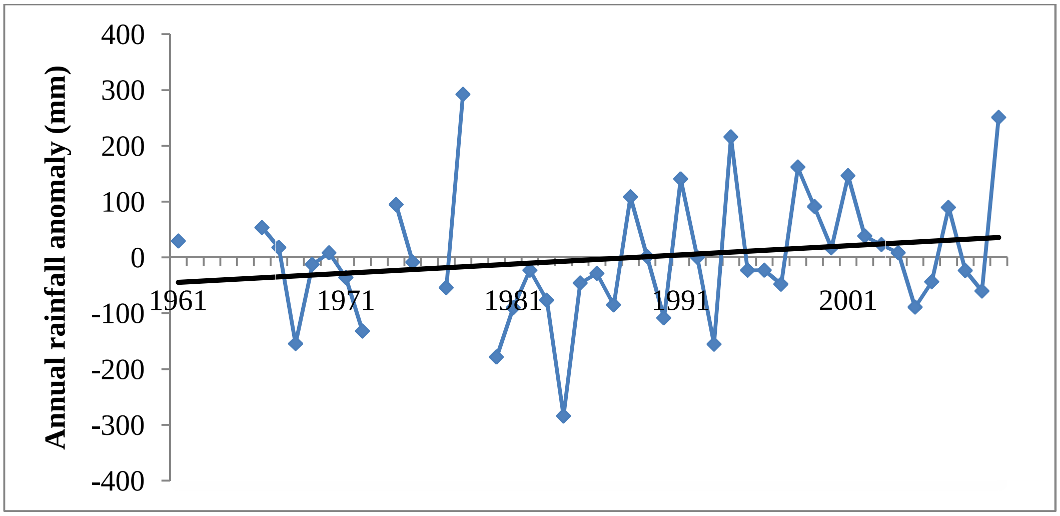

Figure 34: Inter-annual variability of the annual rainfall at Keita.

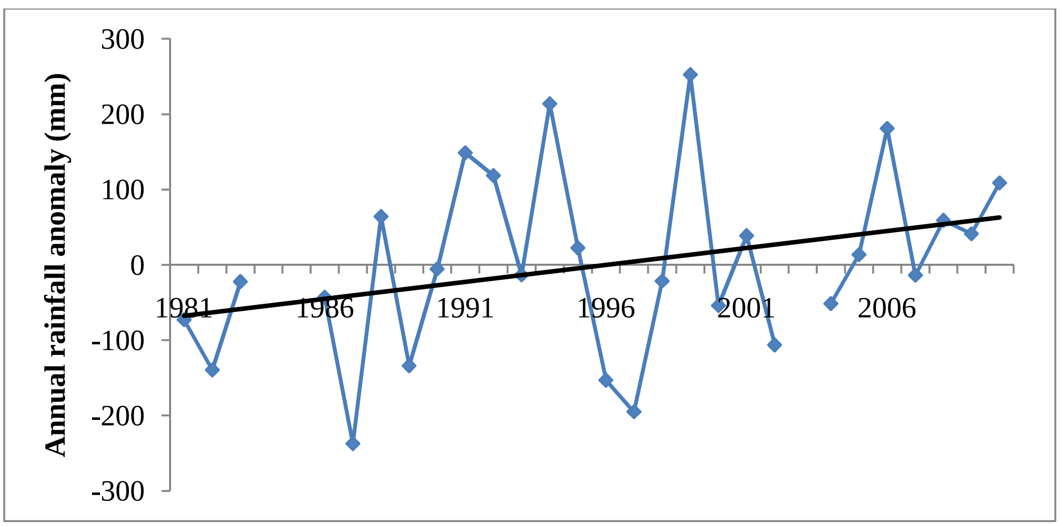

Figure 35: Inter-annual variability of the annual rainfall at Bonkoukou.

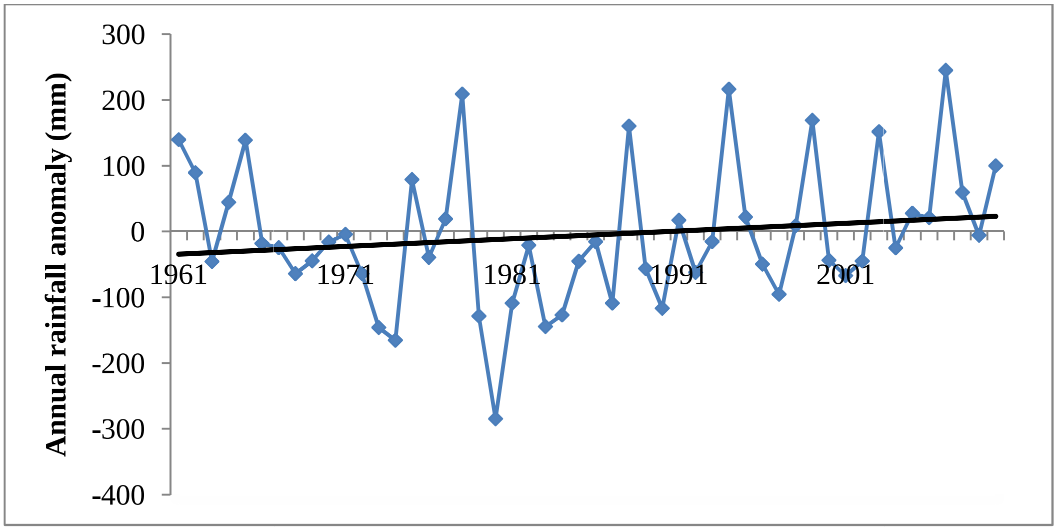

Figure 36: Inter-annual variability of the annual rainfall at Diffa.

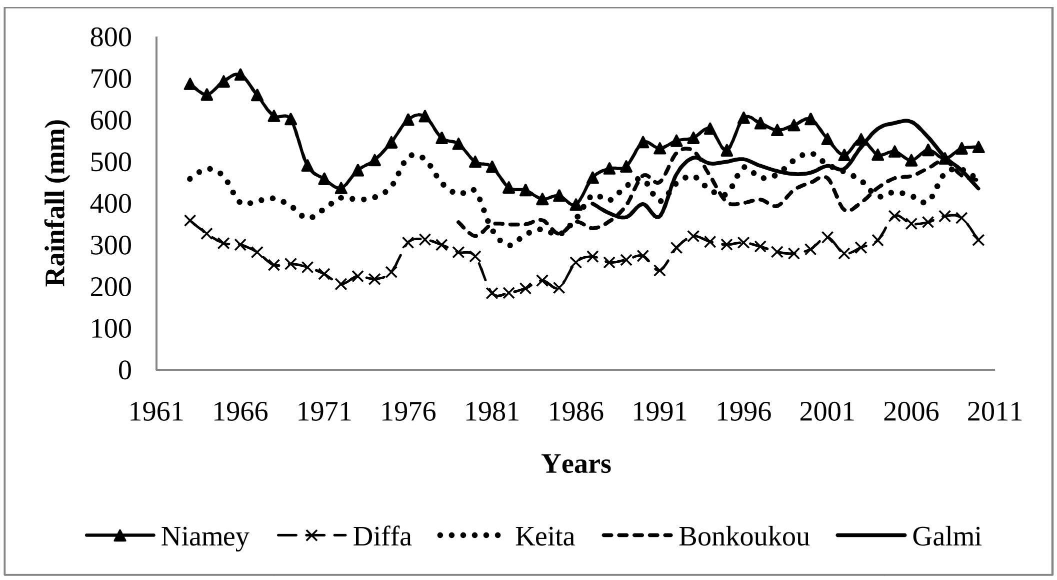

Figure 37: Five-years moving averages of annual rainfall around the study locations.

- ***Variability of the maximum and minimum temperatures***

The monthly mean minimum temperature and maximum temperature of the dry and relatively cold season (October to March) have been computed for each year and each of the meteorological stations in the study area. Then the difference of the average values per year with the overall average has been plotted (Figures 38, 39, 40, and 41). Note that for Bonkoukou, Keita, and Galmi, data from the closest stations were used since temperature data were not recorded. Except for Keita, where the maximum temperature has a slight decreasing trend (which may be related to the relatively high altitude of that zone), those figures show that the minimum temperature as well as the maximum temperature has been increasing. However, the five-year moving average of the mean dry season temperature (Figure 42) shows that the overall increase has been moderated by a cool period during the 1980s for Keita, and two short cool periods around the years 1976 and 2001 for the four other locations. The overall increasing trend of the temperature during the horticultural cropping season may affect the plants' phenology, the yield patterns, and the water demand due to the possible increase in the reference evapotranspiration.

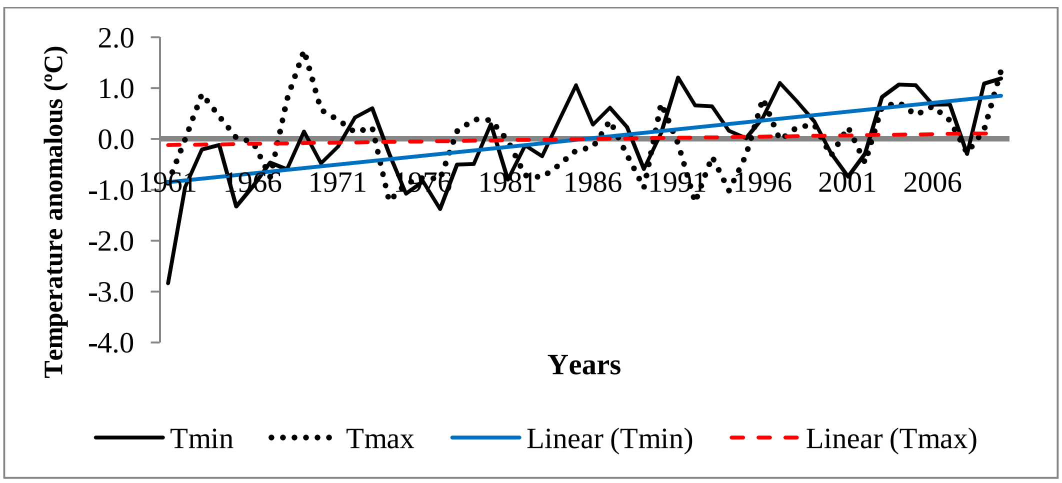

Figure 38: Inter-annual variability of the cool dry season minimum and maximum temperature for Niamey & Bonkoukou.

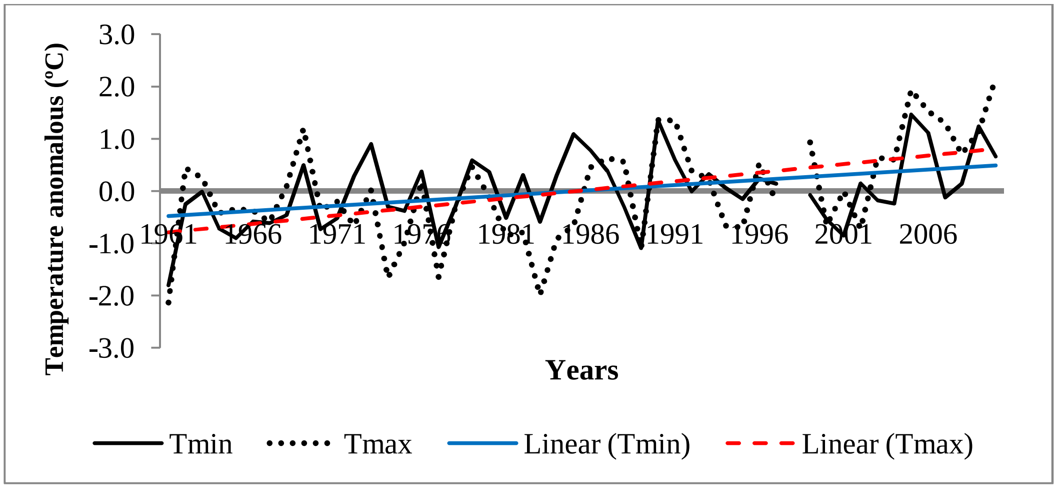

Figure 39: Inter-annual variability of the cool dry season minimum and maximum temperature for Diffa.

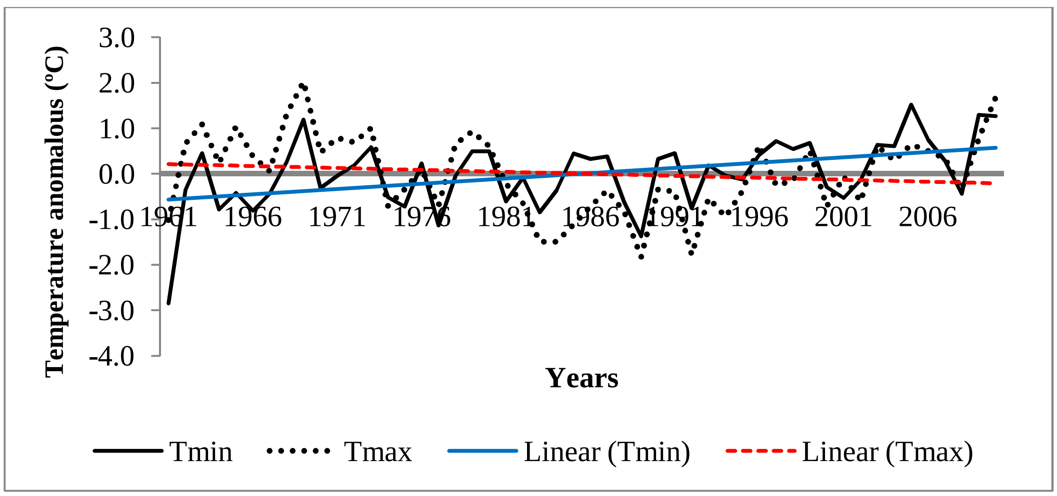

Figure 40: Inter-annual variability of the cool dry season minimum and maximum temperature for Keita.

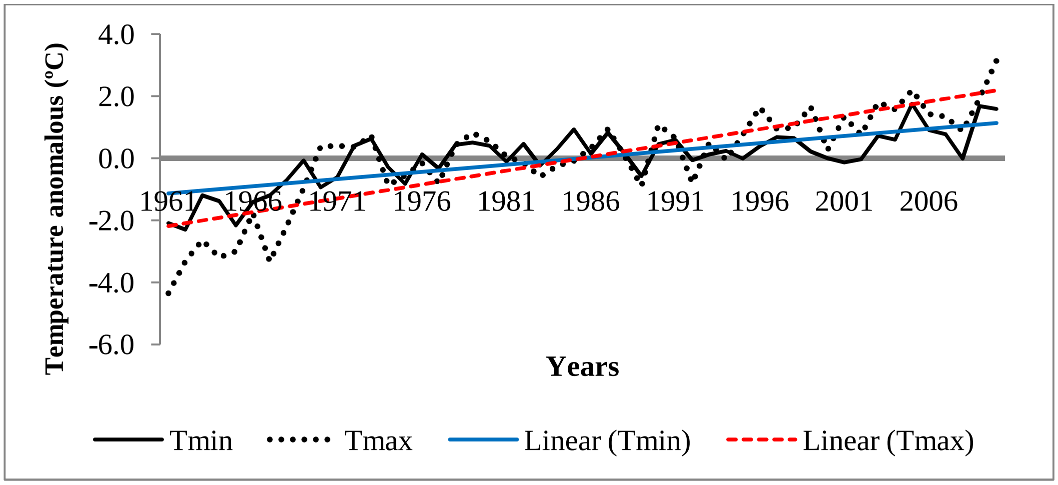

Figure 41: Inter-annual variability of the cool dry season minimum and maximum temperature for Galmi.

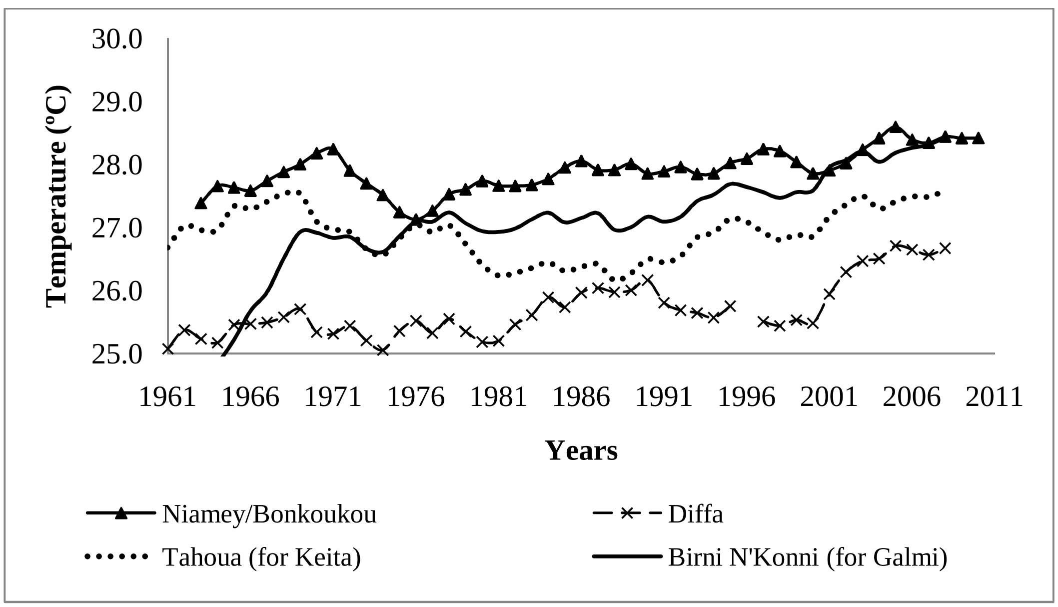

Figure 42: Five-year moving averages of the mean temperature during the cool and dry season around the study locations.

4.2.2. Irrigation water requirements by mid-century and end century

The water balance simulations with DSSAT resulted in very low values of the crops irrigation water needs (Table 10) compared to values found by field experiments by Lennart et al. (2010) and with consideration to the local evapotranspiration rate. That underestimation of the irrigation requirements may be explained by the limitations of the DSSAT models to simulate properly the soil water balance parameters under severe environmental stress as reported previously by Ines et al. (2001) and/or the low empirical soil hydraulic conductivity coefficients associated with those models leading to low root water uptake estimates (De Faria et al., 2003). Indeed, as mentioned in the method section, the DSSAT default sandy loam soil profile has been used in the present study. Due to those discrepancies, the water balance simulation results from DSSAT were not considered in this analysis.

Table 5: Simulated irrigation water requirements (IR) for three climatic timelines from DSSAT crop models.

Location	Crop	Historical Average Irrigation Requirement (mm)	Mid-century Average Irrigation Requirement (mm)	ΔIR mid-century (%)	End-century Average Irrigation Requirement (mm)	ΔIR end-century (%)
Niamey	**Cabbage**	324	359	11	433	34
Bonkoukou	**Potato**	858	736	-13	680	-20
Keita	**Tomato**	287	258	-10	249	-13
Diffa	**Sweet pepper**	480	488	2	394	-18

Table 11 summarizes the average seasonal gross irrigation requirements for each crop and location for mid-century and end-century compared to the current irrigation water needs as simulated by the CROPWAT model. More detailed results are in Appendices E.

The seasonal irrigation requirements for cabbage and potato were estimated as 808 and 1226 mm respectively and increases by 7% at mid-century and 11% by end of the century. The lowest change of the seasonal gross irrigation water requirements were obtained for onion and sweet pepper with 2% and 3% increase by mid-century; and 7% and 5% increase by the end of the century respectively.

The relatively low increase in the average irrigation water requirements hide some decrease obtained for some years as it is shown in the detailed results (Appendices E). From those results, it appears that the crop ET decreases as well for the indicated years. Therefore, that decrease in the irrigation water needs may be related to a deceleration in the plants growth rate as response to the increase of temperature.

Table 6: Simulated irrigation requirements (IR) for three different climatic timelines by CROPWAT.

Location	Crop	Historical Average Irrigation Requirement (mm)	Mid-century Average Irrigation Requirement (mm)	ΔIR mid-century (%)	End-century Average Irrigation Requirement (mm)	ΔIR end-century (%)
Niamey	**Cabbage**	808	868	7	898	11
Bonkoukou	**Potato**	1226	1318	7	1361	11
Galmi	**Onion**	623	634	2	667	7
Keita	**Tomato**	1394	1497	7	1547	11
Diffa	**Sweet pepper**	1024	1050	3	1078	5

4.2.3. Impacts of future climate change on crops parameters (growing season length and yields)

Table 12 presents the predicted impacts of climate change on the crop yield as simulated by DSSAT. Assuming the farm management strategies remain constant, decrease of yield is found for all the crops by mid-century and end-century. Note that simulated yield data are not available for onion since a model for that crop is not provided with the DSSAT system and the simulation results from CROPWAT do not include crop yield. Detailed simulated yield for the current, mid-century, and end-century periods are given in Appendices F.

Table 7: Simulated crops yields for three different climatic timelines.

Location*	Crop	Historical Average Crop Yield (kg/ha)	Mid-century Average Yield (kg/ha)	ΔY mid-century (%)	End-century Average Yield (kg/ha)	ΔY end-century (%)
Niamey	**Cabbage**	9659	9286	-4	8436	-13
Bonkoukou	**Potato**	8272	3716	-54	1513	-81
Keita	**Tomato**	6688	4242	-38	2792	-60
Diffa	**Sweet pepper**	8401	7241	-14	6129	-27

*Simulated yield are not available for onion

- ***Effects of climate change on potato***

The largest decrease was observed with potato grown at Bonkoukou with a 54% decrease at mid-century and 81% decrease at end-century. The detailed simulation outputs show 100% loss in tuber yield for certain planting scenarios by the end of the century. That corresponds to an eventual shutdown of the crop. The dramatic decrease in potato yield may be explained by the high sensitivity of the crop to high temperature. Indeed, the tuber growth is significantly and negatively correlated to the temperature change (Pereira and Sock, 2007). While the mean minimum and maximum predicted temperatures during the potato growing season at Bonkoukou are 22.7°C and 38.0 °C (for mid-century) and 24.3 °C and 39.6 °C (for end-century), Pereira et al., (2007) and Vanderhofstadt (2009) reported that the optimum mean temperature for potato growth should be between 15°C and 20 °C. They stated that tuber growth decreases with soil temperatures above 20°C and practically stops for soil temperatures greater than 30°C. Sattelmacher et al. (1990) also found that, for both heat tolerant and heat sensitive clones, the potato root system diminish significantly in size when the temperature in the root zone exceeds 30 °C.

Based on the historical climatic conditions, the early planting dates seem to give higher yield, however the yield remains low for the future climatic conditions across all planting periods (Figure 43).

In order to plan ahead and maintain the cultivation of potato in that area, adaptation strategies should be found. Pereira and Sock (2007) have suggested field management strategies such as high population density, adequate irrigation and mulch, which should maintain the soil temperature cooler. The development of heat tolerant cultivars and the concentration of the cropping zone in the high lands such as the Aïr Mountains (which is already a potato production zone in Niger) would help to maintain the production of that crop in the country.

- ***Effects of climate change on tomato***

There was also a significant decrease in tomato yield which was about 38% by mid-century and 60 % by end-century as result of the temperature increase (Table 12). Abdelmageed et al., (2003) studied the effect of high temperature on tomato growth in controlled environment chamber in Germany and under field conditions in Sudan (semi-arid conditions similar to Niger) and found that the reproductive stage is the most sensitive to high temperatures, which reduce considerably the pollen production during that stage. Starting the tomato growth during the month of November (DOY 310 to 335) gives relatively higher yields in both historical and future climatic periods. There is no significant change in the growing season length between the three climatic periods (Figure 44). That length is 101 days, 94 days and 92 days for historical, mid-century, and end-century periods respectively (Appendix F2).

- ***Effects of climate change on cabbage and sweet pepper***

Sweet pepper and cabbage seem to be the least affected among the four crops for which yield parameters were simulated. Table 12 shows a relatively low decrease rate varying from -4% (mid-century) to -13% (end-century) for cabbage and from -14% (mid-century) to -27% (end-century) for sweet pepper. Figure 45 shows that, in the three climatic scenarios, the relatively maximum yields of sweet pepper are obtained for planting dates between the end of August (DOY 242) to the end of September (DOY 273). For cabbage there is no significant sensitivity of the yield due to the planting date. However for the end-century scenario, the yield starts decreasing for planting dates greater than the DOY 310 corresponding to November 5th (Figure 46) The crop cycle length is not significantly affected by the change of the climate. For cabbage, it goes from 97 days (historical average), to 103 days (mid-century) and 113 days (end-century) while it is around 155 days for sweet pepper in the three climatic scenarios.

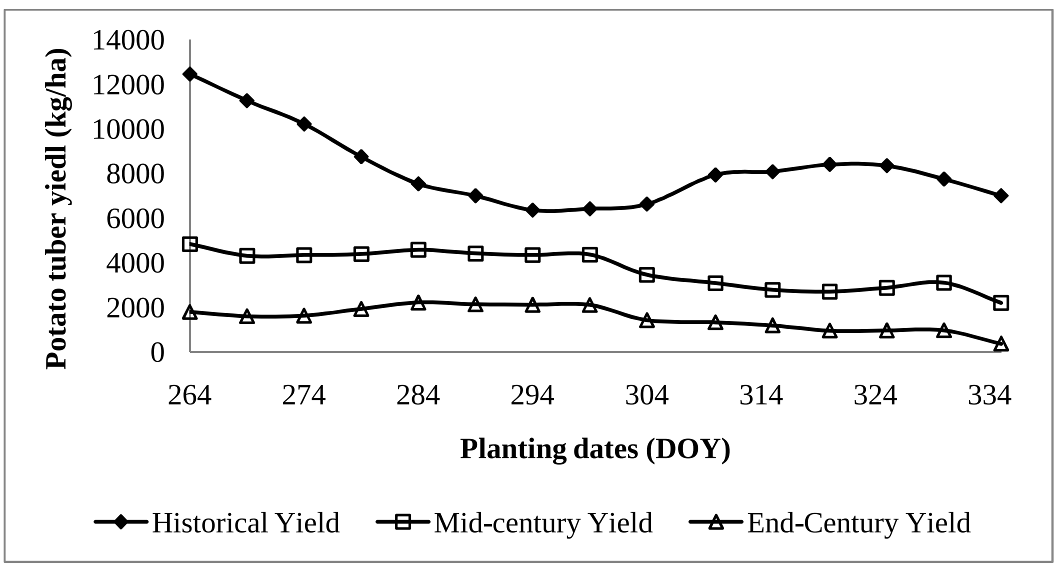

Figure 43: Potato tuber yield as function of the planting dates for the three different climate conditions.

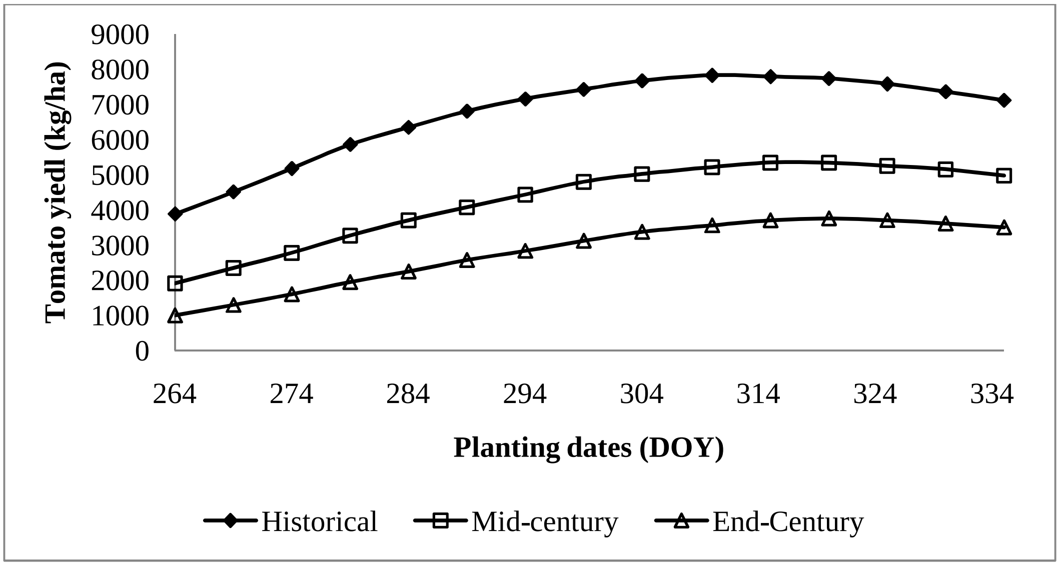

Figure 44: Tomato yield as function of the planting dates for the three different climate conditions.

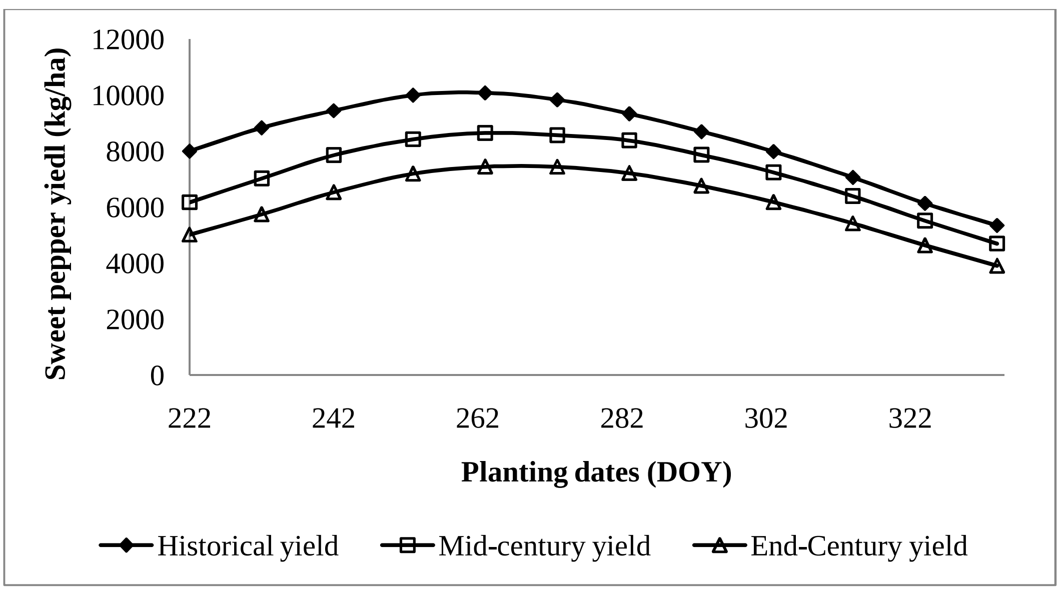

Figure 45: Sweet pepper yield as function of the planting dates for the three different climate conditions.

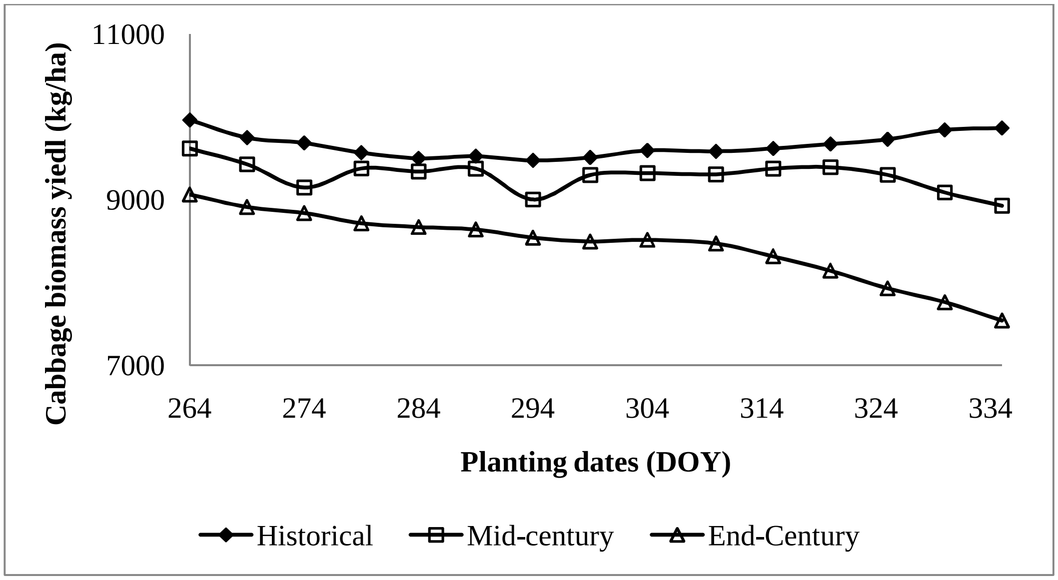

Figure 46: Cabbage top biomass yield as function of the planting dates for the three different climate conditions.

4.3. Limitations of the study

The lack of measured data has constituted the biggest challenge in this study. That did not allow a calibration of the models before their use. Where measured yield data were available, they were average values at district level whereas simulated yield from DSSAT were at site level. Therefore DSSAT was not successful in reproducing the same year to year variability of yield as the observed data. That may be a source of bias in the results obtained. In addition, there are uncertainties associated with the prediction of future climate by the mean of GCMs and the downscaling methods used to retrieve the local predicted data. Due to the inconsistency of the GCMs with their prediction of the rainfall change in the Sahel region, the current rainfall regime was assumed for the future, and the GCMs predictions were ignored. Irrigation requirements for sweet pepper and onion, which have cropping periods starting in the rainy season, will be the most sensitive to any changes in rainfall.

In order to simplify the simulations of the future climate change impacts, fertilizer use and water were assumed to be non-limiting. That might be inaccurate in reality. Other management practices were maintained constant from the historical to the future periods, but those practices may change due to future adaptation plans or farmers year-to-year choices.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The irrigation water requirements for potato, tomato, cabbage, onion, and sweet pepper were investigated respectively at Bonkoukou, Keita, Niamey, Galmi and Diffa in Niger by crop modeling with DSSAT and CROPWAT. Using predicted future climate data as inputs in the crop models, the impacts of the climate change on the irrigation water needs, the crop growth parameters and the crops yields have been analyzed. The optimum planting periods based on the criterion of less water use for maximum yield were also studied.

Based on the 1981-2010 period, the average daily irrigation water requirements found by CROPWAT were 8 mm for potato, tomato, and cabbage; and 6 mm for onion and sweet pepper. The seasonal irrigation water needs would increase by 7% by mid-century and 11% by end-century for cabbage, potato, and tomato. Lesser increases were found for the sweet pepper and onion irrigation water needs with respectively 2% and 3% for mid-century, and 7% and 5% for end-century.

The mean irrigation water needs obtained with DSSAT were 8 mm for potato, and 3 mm for tomato, sweet pepper and cabbage. Compared to the predicted irrigation water needs by DSSAT, the potato, tomato, and sweet pepper irrigation water requirements would decrease by 20%, 13%, and 18% respectively by the end of the century. Conversely, cabbage irrigation requirements are expected to increase by 34 %. According to the local evapotranspiration rate, those irrigation requirement values obtained from DSSAT were low. The underestimation may be related to the

DSSAT soil water balance sub module or/and a mismatch between the DSSAT default sandy loam soil profile that was used and the field real characteristics. Therefore, the water balance simulated parameters from DSSAT were not considered in the analysis.

Maximum simulated yields by DSSAT were obtained for planting periods in November for potato and tomato, while for cabbage there is little sensitivity of the yield to the planting date. For sweet pepper, the growing season starting in September leads to better yield. For all the crops, the yield decrease as a result of the increase in temperature by mid-century and end-century. The largest yield decrease was found for tomato and potato. Potato shows total crop failure by the end of the century for certain planting scenarios.

5.1. Implications of the results and possible adaptation strategies to climate change

The results obtained from the simulations of the irrigation water requirements and crop parameters based on the current climate conditions reveal several implications to improve water management in horticulture in Niger. The study shows that early November would be the optimum planting period to reduce crop irrigation and maximize yield for cabbage, tomato, and potato. Transplanting sweet pepper and onion in early September would be a good management strategy.

Due to the more reasonable estimates of irrigation requirement obtained with CROPWAT compared to DSSAT, the CROPWAT program can be more appropriate to assist farmers in the irrigation management. However, since DSSAT provides more outputs on crop response, its models outputs may allow a better understanding of the crop growth parameters. Those models are suggested to fill the gap of the current lack of dry season crops models at some extension services such as the Agricultural Meteorology department of the Niger National Meteorological Service. The estimates of crop water needs on a ten-day-period basis implemented in the present study will inform the dekadal bulletins released by this service. That would serve as guidance to farmers and irrigation management technicians. However, better access for farmers to climate risk information in general, and new site-specific management tools developed based on these results, is essential.

Based on the possible impacts of the future climate change on horticulture crops in Niger revealed in this study, adaptation strategies are necessary to preserve the sustainability of that type of agriculture. Among those strategies should be the development of heat-tolerant varieties for those areas. Local research centers, such as the Sahelian center of the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT), have started introducing vegetable varieties adapted to the rainy season. Additional similar initiatives should be encouraged as they may mitigate significantly the predicted increase in irrigation water demand. To mitigate the future climate impacts on the agriculture water supply, adequate irrigation management plans should be developed and implemented at the national level.

In areas where difficulties are expected in growing heat sensitive crops such as potato and tomato, switching to other cropping systems may be an adaptation strategy. Sweet pepper and onion (though onion yields were not simulated, it has better adaptability potential in terms of irrigation water needs) should be extended in the other parts of the country, since they are the major horticulture cash crops and because they seem to be more resistant to the predicted heat stress.

5.2. Recommendations

The main recommendation for future studies based on the present results is to conduct field experiments in order to calibrate the DSSAT and CROPWAT models for those areas. The extension of the meteorological data observation network would add more precision to future work.

The development of better climate prediction models at the regional (or even at the national) level would reduce the uncertainties related in the estimation of future climate data. It would be easier to handle this type of analysis with integrated climate and crop models.

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APPPENDICES

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APPENDICES A: Crops and soil inputs files parameterization for DSSAT

Appendix A1: Main potato crop and soil input parameters used with DSSAT

Cultivar	: Desiree
Planting dates (DOY)	: 20-Sep, 25-Sep, 30-Sep, 05-Oct, 10-Oct, 15-Oct, 20-Oct, 25-Oct, 30-Oct, 05-Nov, 10-Nov, 15-Nov, 20-Nov, 25-Nov, 30-Nov
Planting density (plants/m^2)	: 5.1/m^2
Rows spacing (cm)	: 86
N-fertilizer use	: no limit
Irrigation option	: Automatic irrigation – Refill profile
Mgmt depth (cm)	: 50
Max allowable depletion (%)	: 80
Soil profile used	: DSSAT default deep sandy loam
Soil albedo	: 0.21
Evaporation limit (mm)	: 6.00
Runoff curve number	: 60.00
Drainage rate	: 0.60

Appendix A2: Main tomato crop and soil input parameters used with DSSAT

Cultivar	: Sunny S-D
Planting dates (DOY)	: 20-Sep, 25-Sep, 30-Sep, 05-Oct, 10-Oct, 15-Oct, 20-Oct, 25-Oct, 30-Oct, 05-Nov, 10-Nov, 15-Nov, 20-Nov, 25-Nov, 30-Nov
Planting method	: Transplants
Planting density (plants/m^2)	: 1/m^2
Rows spacing (cm)	: 50
N-fertilizer use	: no limit
Irrigation option	: Automatic irrigation – Refill profile
Mgmt depth (cm)	: 45
Max allowable depletion (%)	: 50
Soil profile used	: DSSAT default medium sandy loam
Soil albedo	: 0.13
Evaporation limit (mm)	: 6.00
Runoff curve number	: 70.00
Drainage rate	: 0.50

Appendix A3: Main sweet pepper crop and soil input parameters used with DSSAT

Cultivar	: Biscayne
Planting dates (DOY)	: 10-Aug, 20-Aug, 30-Aug, 10-Sep, 20-Sep, 30-Sep, 10-Oct, 20-Oct, 30-Oct, 10-Nov, 20-Nov, 30-Nov
Planting method	: Transplants
Planting density (plants/m^2)	: 4.3/m^2
Rows spacing (cm)	: 75
N-fertilizer use	: no limit
Irrigation option	: Automatic irrigation – Refill profile
Mgmt depth (cm)	: 30
Max allowable depletion (%)	: 40
Soil profile used	: DSSAT default deep sandy loam
Soil albedo	: 0.21
Evaporation limit (mm)	: 6.00
Runoff curve number	: 60.00
Drainage rate	: 0.60

Appendix A4: Main cabbage crop and soil input parameters used with DSSAT

Cultivar	: CG
Planting dates (DOY)	: 20-Sep, 25-Sep, 30-Sep, 05-Oct, 10-Oct, 15-Oct, 20-Oct, 25-Oct, 30-Oct, 05-Nov, 10-Nov, 15-Nov, 20-Nov, 25-Nov, 30-Nov
Planting method	: Transplants
Planting density (plants/m^2)	: 5.7/m^2
Rows spacing (cm)	: 46
N-fertilizer use	: no limit
Irrigation option	: Automatic irrigation – Refill profile
Mgmt depth (cm)	: 30
Max allowable depletion (%)	: 50
Soil profile used	: DSSAT default deep sandy loam
Soil albedo	: 0.21
Evaporation limit (mm)	: 6.00
Runoff curve number	: 60.00
Drainage rate	: 0.60

APPENDICES B: **Simulated dekadal crop irrigation requirements from CROPWAT**

Appendix B1: Distribution of the dekadal irrigation water requirements (mm/dekad) for potato at Bonkoukou.

	Planting on 10/01			Planting on 11/01			Planting on 12/01			
Dekads	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Overall average**
1	47	3	39	48	31	40	50	32	41	**40**
2	49	27	41	51	33	41	53	36	42	**41**
3	56	12	47	53	34	41	56	39	47	**45**
4	64	42	54	64	42	52	87	25	56	**54**
5	82	46	65	82	47	64	116	33	69	**66**
6	93	50	71	95	51	79	145	40	92	**81**
7	91	54	73	120	32	76	133	56	93	**80**
8	95	58	75	131	35	77	164	60	96	**83**
9	95	62	79	142	38	90	131	64	82	**84**
10	112	32	75	128	67	89	164	68	103	**89**
11	114	32	69	144	60	85	150	69	94	**83**
12	109	29	70	102	51	64	144	68	93	**76**
13	78	32	43	111	52	69	92	44	62	**58**

Appendix B2: Distribution of the dekadal irrigation water requirements (mm/dekad) for tomato at Keita.

	Planting on 10/01			Planting on 12/01			Planting on 01/21			
Dekads	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Overall average**
1	57	0	35	53	33	42	53	36	44	**40**
2	70	7	40	56	33	42	54	31	41	**41**
3	73	14	47	54	38	46	51	36	43	**45**
4	63	39	49	63	36	48	69	45	56	**51**
5	75	44	59	70	48	58	81	47	64	**60**
6	86	45	65	96	60	76	97	55	75	**72**
7	92	56	71	107	61	84	89	56	71	**75**
8	101	57	75	115	63	88	116	77	94	**86**
9	97	66	81	93	59	75	127	74	94	**83**
10	102	56	76	117	78	95	138	81	108	**93**
11	93	65	78	128	76	94	129	79	98	**90**
12	109	68	87	137	81	108	112	73	91	**95**
13	99	57	79	118	72	90	123	40	85	**85**
14	98	54	74	97	62	78	108	49	75	**76**
15	20	8	14	42	3	29	34	0	25	**23**

Appendix B3: Distribution of the dekadal irrigation water requirements (mm/dekad) for onion at Galmi.

	Planting on 10/01			Planting on 12/11			Planting on 02/21			
Dekads	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Overall average**
1	44	14	33	45	28	35	41	26	32	**33**
2	42	14	35	47	33	39	55	32	40	**38**
3	49	28	43	47	27	38	59	34	43	**41**
4	49	34	41	51	30	41	71	44	55	**46**
5	50	38	43	65	43	51	68	45	54	**50**
6	53	31	43	65	45	54	68	35	56	**51**
7	53	36	44	70	33	55	76	28	58	**52**
8	58	35	46	62	37	47	69	34	58	**50**
9	60	42	50	83	46	59	66	35	56	**55**
10	57	33	46	84	47	60	74	14	58	**55**
11	45	26	36	80	48	62	70	8	46	**48**

Appendix B4: Distribution of the dekadal irrigation water requirements (mm/dekad) for sweet pepper at Diffa.

	Planting on 09/01			Planting on 11/11			Planting on 01/21			
Dekads	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Overall average**
1	47	0	22	52	34	43	44	30	37	**34**
2	47	0	26	51	32	40	44	30	36	**34**
3	44	1	33	47	31	38	49	32	39	**37**
4	50	16	39	52	33	41	49	29	36	**39**
5	59	37	48	65	43	50	64	46	54	**51**
6	64	40	57	71	45	54	87	51	62	**58**
7	64	40	56	73	49	60	94	61	74	**63**
8	65	42	54	84	55	70	90	62	72	**65**
9	64	40	49	85	56	68	95	52	71	**63**
10	60	38	47	94	59	72	91	58	71	**64**
11	60	38	48	87	50	61	80	51	71	**60**
12	66	42	50	100	71	84	82	44	70	**68**
13	61	39	47	119	69	83	86	45	73	**68**
14	54	37	45	102	68	82	78	31	58	**62**
15	43	28	35	76	52	60	67	21	50	**49**

Appendix B5: Distribution of the dekadal irrigation water requirements (mm/dekad) for cabbage at Niamey.

	Planting on 10/01			Planting on 11/11			Planting on 12/21			
Dekads	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**	**Overall average**
1	47	8	37	52	33	41	73	22	50	**43**
2	49	11	39	52	33	40	67	42	50	**43**
3	60	34	51	55	36	45	94	41	57	**51**
4	65	46	55	68	46	54	88	45	56	**55**
5	79	50	62	79	54	67	126	60	80	**70**
6	82	51	64	106	27	66	134	37	84	**71**
7	80	50	65	115	30	67	149	72	98	**77**
8	83	55	65	124	32	79	128	65	86	**77**
9	81	55	68	109	63	76	131	56	81	**75**
10	76	21	49	102	41	59	126	47	71	**60**

APPENDICES C: Simulated seasonal crop irrigation requirements from CROPWAT

Appendix C1: Potato crop seasonal irrigation water requirements simulated by CROPWAT.

Years	Seasonal Irrigation Requirement . - P1*	Seasonal Irrigation Requirement . – P2**	Seasonal Irrigation Requirement – P3***
	mm	**mm**	**mm**
1981	840	994	1164
1982	710	743	809
1983	876	1158	1436
1984	740	778	852
1986	703	742	827
1987	737	755	825
1988	740	779	869
1989	906	985	1085
1990	832	920	1074
1991	885	880	923
1992	915	994	1106
1993	864	927	1025
1994	794	846	930
1995	820	857	955
1996	802	826	895
1997	916	997	1060
1998	773	873	1025
1999	865	920	1021
2000	669	749	924
2001	907	940	991
2002	818	890	975
2004	809	854	959
2005	748	860	945
2006	793	839	935
2007	749	824	936
2008	771	828	945
2009	731	806	901
2010	770	818	899
Average	**803**	**871**	**975**

*P1 : Planting on 10/01

**P2 : Planting on 11/01

***P3 :Planting on 12/01

Appendix C2: Tomato crop seasonal irrigation water requirements simulated by CROPWAT.

Years	Seasonal Irrigation Requirement. - P1*	Seasonal Irrigation Requirement. – P2**	Seasonal Irrigation Requirement. – P3***
	mm	**mm**	**mm**
1980	841	919	925
1981	1006	1134	1149
1982	879	1014	1034
1983	1004	1104	1167
1984	1092	1181	1213
1985	1136	1197	1216
1986	812	944	966
1987	861	950	995
1988	935	1028	1033
1989	1074	1116	1107
1990	1009	1171	1173
1991	1009	1083	1062
1992	970	1053	1061
1993	921	1047	1086
1994	775	1012	1053
1995	850	943	947
1996	859	969	980
1997	808	937	933
1998	813	974	984
1999	783	860	890
2000	804	1004	1029
2001	891	943	942
2002	958	1057	1061
2003	1007	1136	1169
2004	1066	1238	1258
2005	1050	1192	1149
2006	1046	1145	1160
2007	916	1103	1119
2008	901	1107	1134
2009	847	1017	1013
2010	911	1050	1031
Average	**930**	**1052**	**1066**

*P1 : Planting on 10/01

**P2 : Planting on 12/01

***P3 :Planting on 01/21

Appendix C3: Sweet pepper crop seasonal irrigation water requirements simulated by CROPWAT

Years	Seasonal Irrigation Requirement. - P1*	Seasonal Irrigation Requirement – P2**	Seasonal Irrigation Requirement – P3***
	mm	mm	mm
1986	722	1092	1070
1987	678	887	917
1988	696	912	825
1989	673	881	809
1990	635	856	827
1991	661	871	817
1992	727	981	964
1993	707	986	975
1994	649	965	945
1995	694	952	941
1996	678	1014	938
1997	666	881	858
1999	542	817	801
2000	624	806	813
2001	599	806	795
2002	577	819	827
2003	593	822	761
2004	643	839	854
2005	670	912	819
2006	641	952	909
2007	656	868	789
2008	680	923	889
2009	637	898	889
2010	716	1014	946
Average	**657**	**906**	**874**

*P1 : Planting on 09/01

**P2 : Planting on 11/11

***P3 :Planting on 01/21

Appendix C4: Cabbage crop seasonal irrigation water requirements simulated by CROPWAT

Years	Seasonal Irrigation Requirement - P1*	Seasonal Irrigation Requirement – P2**	Seasonal Irrigation Requirement – P3***
	mm	**mm**	**mm**
1980	531	572	722
1981	531	684	889
1982	497	506	584
1983	519	774	1115
1984	517	543	625
1985	541	570	633
1986	475	508	616
1987	516	524	599
1988	524	529	634
1989	611	682	793
1990	578	622	798
1991	622	616	653
1992	642	691	788
1993	605	638	744
1994	540	582	657
1995	579	598	677
1996	568	567	646
1997	612	676	730
1998	525	596	759
1999	595	634	764
2000	521	466	741
2001	646	659	713
2002	557	629	702
2003	570	596	713
2004	571	596	687
2005	519	586	692
2006	549	576	709
2007	512	569	670
2008	543	575	707
2009	519	545	675
2010	510	570	666
Average	**553**	**596**	**713**

*P1 : Planting on 10/01

**P2 : Planting on 11/11

***P3 : Planting on 12/21

Appendix C5: Onion crop seasonal irrigation water requirements simulated by CROPWAT

Years	Seasonal Irrigation Requirement - P1*	Seasonal Irrigation Requirement – P2**	Seasonal Irrigation Requirement – P3***
	mm	**mm**	**mm**
1987	420	481	587
1988	467	579	613
1990	491	671	637
1993	407	494	582
1994	405	509	572
1995	423	491	522
1996	469	513	567
1997	472	551	485
1998	516	610	624
1999	502	563	583
2000	485	606	628
2001	495	576	630
2002	465	571	520
2003	492	556	569
2004	493	576	494
2005	465	550	496
2006	447	501	545
2007	445	488	515
2008	423	486	494
2009	406	485	534
2010	455	498	475
Average	**459**	**541**	**556**

*P1 : Planting on 10/01

**P2 : Planting on 12/11

***P3 : Planting on 02/21

APPENDICES D: ANOVA tables for comparison of average dekadal irrigation requirements

Appendix D1: ANOVA tables for comparison of average dekadal irrigation requirements –Potato at Bonkoukou

Dekad 1

Source	df	SS	MS	F
Trt. Err.	2	31	16	**0.343**
Exp. Err.	81	3661	45	
Total	83	3692		

… Dekad 2

Source	df	SS	MS	F
Trt. Err.	2	42	21	**0.966**
Exp. Err.	81	1781	22	
Total	83	1824		

Dekad 3

Source	df	SS	MS	F
Trt. Err.	2	553	276	**7.166**
Exp. Err.	81	3125	39	
Total	83	3678		

… Dekad 4

Source	df	SS	MS	F
Trt. Err.	2	248	124	**1.916**
Exp. Err.	81	5239	65	
Total	83	5486		

Dekad 5

Source	df	SS	MS	F
Trt. Err.	2	341	171	**1.453**
Exp. Err.	81	9507	117	
Total	83	9848		

Dekad 6

Source	df	SS	MS	F
Trt. Err.	2	5963	2982	**15.98**
Exp. Err.	81	15117	187	
Total	83	21080		

Dekad 7

Source	df	SS	MS	F
Trt. Err.	2	6457	3228	**15.47**
Exp. Err.	81	16905	209	
Total	83	23362		

Dekad 8

Source	df	SS	MS	F
Trt. Err.	2	7930	3965	**15.92**
Exp. Err.	81	20177	249	
Total	83	28107		

Dekad 9

Source	df	SS	MS	F
Trt. Err.	2	1807	904	**4.363**
Exp. Err.	81	16777	207	
Total	83	18585		

Dekad 10

Source	df	SS	MS	F
Trt. Err.	2	11084	5542	**21.320**
Exp. Err.	81	21055	260	
Total	83	32139		

Dekad 11

Source	df	SS	MS	F
Trt. Err.	2	8651	4325	**18.32**
Exp. Err.	81	19120	236	
Total	83	27771		

Dekad 12

Source	df	SS	MS	F
Trt. Err.	2	13067	6534	**34.99**
Exp. Err.	81	15125	187	
Total	83	28193		

Dekad 13

Source	df	SS	MS	F
Trt. Err.	2	10094	5047	**10.64**
Exp. Err.	81	38413	474	
Total	83	48507		

Appendix C2: ANOVA tables for comparison of average dekadal irrigation requirements – Tomato at Keita.

Dekad 1

Source	df	SS	MS	F
Trt. Err.	2	1638	819	**11.39**
Exp. Err.	90	6470	72	
Total	92	8108		

… Dekad 2

Source	df	SS	MS	F
Trt. Err.	2	61	30	**0.538**
Exp. Err.	69	3889	56	
Total	71	3949		

Dekad 3

Source	df	SS	MS	F
Trt. Err.	2	258	129	**2.484**
Exp. Err.	69	3581	52	
Total	71	3839		

… Dekad 4

Source	df	SS	MS	F
Trt. Err.	2	1015	508	**12.55**
Exp. Err.	69	2792	40	
Total	71	3807		

Dekad 5

Source	df	SS	MS	F
Trt. Err.	2	717	358	**5.779**
Exp. Err.	69	4278	62	
Total	71	4994		

Dekad 6

Source	df	SS	MS	F
Trt. Err.	2	2153	1077	**9.711**
Exp. Err.	69	7651	111	
Total	71	9804		

Dekad 7

Source	df	SS	MS	F
Trt. Err.	2	3244	1622	**16.01**
Exp. Err.	69	6992	101	
Total	71	10236		

Dekad 8

Source	df	SS	MS	F
Trt. Err.	2	6300	3150	**23.94**
Exp. Err.	69	9078	132	
Total	71	15377		

Dekad 9

Source	df	SS	MS	F
Trt. Err.	2	5849	2924	**24.83**
Exp. Err.	69	8126	118	
Total	71	13975		

Dekad 10

Source	df	SS	MS	F
Trt. Err.	2	16671	8335	**64.27**
Exp. Err.	69	8949	130	
Total	71	25620		

Dekad 11

Source	df	SS	MS	F
Trt. Err.	2	6818	3409	**23.75**
Exp. Err.	69	9905	144	
Total	71	16724		

Dekad 12

Source	df	SS	MS	F
Trt. Err.	2	7318	3659	**25.63**
Exp. Err.	69	9852	143	
Total	71	17169		

Dekad 13

Source	df	SS	MS	F
Trt. Err.	2	2115	1058	**6.346**
Exp. Err.	69	11501	167	
Total	71	13616		

Dekad 14

Source	df	SS	MS	F
Trt. Err.	2	309	154	**1.085**
Exp. Err.	69	9810	142	
Total	71	10119		

Appendix C2 (continued)

Decade 15

Source	**df**	**SS**	**MS**	**F**
Trt. Err.	2	3492.989	1746.5	**44.783**
Exp. Err.	69	2690.951	39.0	
Total	71	6183.94		

Appendix D3: ANOVA tables for comparison of average dekadal irrigation requirements –Sweet pepper at Diffa

Dekad 1

Source	df	SS	MS	F
Trt. Err.	2	5782	2891	**36.17**
Exp. Err.	69	5515	80	
Total	71	11298		

… Dekad 2

Source	df	SS	MS	F
Trt. Err.	2	2225	1112	**17.40**
Exp. Err.	69	4410	64	
Total	71	6635		

Dekad 3

Source	df	SS	MS	F
Trt. Err.	2	468	234	**4.287**
Exp. Err.	69	3763	55	
Total	71	4231		

… Dekad 4

Source	df	SS	MS	F
Trt. Err.	2	379	190	**4.633**
Exp. Err.	69	2825	41	
Total	71	3205		

Dekad 5

Source	df	SS	MS	F
Trt. Err.	2	431	215	**7.222**
Exp. Err.	69	2058	30	
Total	71	2489		

Dekad 6

Source	df	SS	MS	F
Trt. Err.	2	699	350	**7.872**
Exp. Err.	69	3064	44	
Total	71	3763		

Dekad 7

Source	df	SS	MS	F
Trt. Err.	2	4641	2321	**48.37**
Exp. Err.	69	3310	48	
Total	71	7951		

Dekad 8

Source	df	SS	MS	F
Trt. Err.	2	4929	2464	**52.96**
Exp. Err.	69	3211	47	
Total	71	8140		

Dekad 9

Source	df	SS	MS	F
Trt. Err.	2	6849	3425	**58.63**
Exp. Err.	69	4031	58	
Total	71	10880		

Dekad 10

Source	df	SS	MS	F
Trt. Err.	2	9379	4690	**80.34**
Exp. Err.	69	4028	58	
Total	71	13407		

Dekad 11

Source	df	SS	MS	F
Trt. Err.	2	6473	3236	**75.08**
Exp. Err.	69	2974	43	
Total	71	9447		

Dekad 12

Source	df	SS	MS	F
Trt. Err.	2	13637	6818	**107.9**
Exp. Err.	69	4360	63	
Total	71	17997		

Dekad 13

Source	df	SS	MS	F
Trt. Err.	2	16933	8467	**101.3**
Exp. Err.	69	5768	84	
Total	71	22701		

Dekad 14

Source	df	SS	MS	F
Trt. Err.	2	16212	8106	**92.25**
Exp. Err.	69	6063	88	
Total	71	22275		

Appendix C3 (continued)

Dekad 15

Source	**df**	**SS**	**MS**	**F**
Trt. Err.	2	7238	3619	**60.36**
Exp. Err.	69	4137	60	
Total	71	11375		

Appendix D4: ANOVA tables for comparison of average dekadal irrigation requirements – Cabbage at Niamey

Dekad 1

Source	df	SS	MS	F
Trt. Err.	2	2658	1329	**22.15**
Exp. Err.	90	5400	60	
Total	92	8058		

… Dekad 2

Source	df	SS	MS	F
Trt. Err.	2	2158	1079	**21.48**
Exp. Err.	69	3465	50	
Total	71	5623		

Dekad 3

Source	df	SS	MS	F
Trt. Err.	2	2230	1115	**21.91**
Exp. Err.	69	3511	51	
Total	71	5741		

… Dekad 4

Source	df	SS	MS	F
Trt. Err.	2	48	24	**0.488**
Exp. Err.	69	3399	49	
Total	71	3447		

Dekad 5

Source	df	SS	MS	F
Trt. Err.	2	5353	2677	**30.33**
Exp. Err.	69	6090	88	
Total	71	11443		

Dekad 6

Source	df	SS	MS	F
Trt. Err.	2	7365	3682	**23.50**
Exp. Err.	69	10811	157	
Total	71	18176		

Dekad 7

Source	df	SS	MS	F
Trt. Err.	2	21574	10787	**63.91**
Exp. Err.	69	11646	169	
Total	71	33220		

Dekad 8

Source	df	SS	MS	F
Trt. Err.	2	6770	3385	**23.20**
Exp. Err.	69	10069	146	
Total	71	16838		

Dekad 9

Source	df	SS	MS	F
Trt. Err.	2	2845	1422	**10.90**
Exp. Err.	69	9003	130	
Total	71	11847		

Dekad 10

Source	df	SS	MS	F
Trt. Err.	2	7956	3978	**26.96**
Exp. Err.	69	10182	148	
Total	71	18138		

Appendix D5: ANOVA tables for comparison of average dekadal irrigation requirements –Onion at Galmi

Dekad 1

Source	df	SS	MS	F
Trt. Err.	2	128	64	**1.474**
Exp. Err.	60	2609	43	
Total	62	2737		

… Dekad 2

Source	df	SS	MS	F
Trt. Err.	2	267	133	**3.667**
Exp. Err.	60	2181	36	
Total	62	2448		

Dekad 3

Source	df	SS	MS	F
Trt. Err.	2	301	151	**5.223**
Exp. Err.	60	1731	29	
Total	62	2033		

… Dekad 4

Source	df	SS	MS	F
Trt. Err.	2	2771	1386	**45.32**
Exp. Err.	60	1834	31	
Total	62	4605		

Dekad 5

Source	df	SS	MS	F
Trt. Err.	2	1344	672	**26.88**
Exp. Err.	60	1500	25	
Total	62	2844		

Dekad 6

Source	df	SS	MS	F
Trt. Err.	2	2159	1079	**23.71**
Exp. Err.	60	2731	46	
Total	62	4890		

Dekad 7

Source	df	SS	MS	F
Trt. Err.	2	2243	1121	**15.72**
Exp. Err.	60	4281	71	
Total	62	6524		

Dekad 8

Source	df	SS	MS	F
Trt. Err.	2	1951	975	**23.95**
Exp. Err.	60	2444	41	
Total	62	4395		

Dekad 9

Source	df	SS	MS	F
Trt. Err.	2	926	463	**7.223**
Exp. Err.	60	3846	64	
Total	62	4773		

Dekad 10

Source	df	SS	MS	F
Trt. Err.	2	2418	1209	**10.68**
Exp. Err.	60	6794	113	
Total	62	9212		

Dekad 11

Source	df	SS	MS	F
Trt. Err.	2	7332	3666	**32.82**
Exp. Err.	60	6702	112	
Total	62	14034		

APPENDICES E: **Simulated gross irrigation requirements (IR) for historical, mid-century, and end-century time periods based on CROPWAT**

Appendix E1: Comparison of the potato historical IR to mid-century and end-century IR

	Historical				Mid-century					End-century				
Year	**Growing cycle length**	**ETc**	**Crop IR**	**Gross IR**	**Growing cycle length**	**ETc**	**Crop IR**	**Gross IR**	**Variation of Gross IR (%)**	**Growing cycle length**	**ETc**	**Crop Irr**	**Gross Irr**	**Variation of Gross Irr(%)**
1981	127	1014	1014	1418	129	1059	1059	1501	6	129	1103	1103	1565	10
1982	121	745	745	995	127	807	807	1131	14	125	832	832	1149	15
1983	127	1200	1200	1670	128	1455	1455	2043	22	129	1518	1518	2150	29
1984	127	780	780	1095	128	848	848	1198	9	128	874	874	1234	13
1986	127	750	750	1047	122	800	800	1075	3	127	826	826	1153	10
1987	125	764	764	1047	126	786	786	1086	4	126	811	811	1121	7
1988	123	788	788	1064	129	865	865	1225	15	125	893	893	1229	15
1989	126	989	989	1378	125	1155	1155	1601	16	127	1197	1197	1682	22
1990	128	937	937	1319	128	1016	1016	1429	8	127	1050	1050	1461	11
1991	123	879	879	1200	126	942	942	1313	9	123	972	972	1326	11
1992	128	1007	1007	1418	124	1122	1122	1533	8	126	1162	1162	1612	14
1993	129	937	937	1329	129	1039	1039	1475	11	128	1060	1060	1492	12
1994	123	849	849	1156	122	889	889	1202	4	126	920	920	1284	11
1995	123	862	862	1175	126	909	909	1267	8	124	940	940	1294	10
1996	124	830	830	1130	128	846	846	1190	5	129	873	873	1238	10
1997	127	1001	1001	1408	124	1056	1056	1455	3	125	1094	1094	1518	8
1998	127	884	884	1237	127	945	945	1323	7	123	978	978	1329	7
1999	127	928	928	1299	123	989	989	1344	3	123	1023	1023	1392	7
2000	128	769	769	1075	125	846	846	1139	6	128	876	876	1224	14
2001	122	940	940	1279	124	993	993	1375	8	124	1028	1028	1424	11
2002	129	898	898	1274	128	949	949	1340	5	125	983	983	1360	7
2004	125	864	864	1185	129	893	893	1265	7	126	923	923	1275	8
2005	128	870	870	1228	128	904	904	1277	4	123	935	935	1269	3
2006	128	845	845	1190	125	875	875	1204	1	124	903	903	1233	4
2007	127	835	835	1165	126	900	900	1246	7	128	929	929	1307	12
2008	128	839	839	1178	123	897	897	1210	3	127	927	927	1294	10
2009	128	814	814	1143	126	815	815	1128	-1	124	842	842	1143	0
Average	**126**	**882**	**882**	**1226**	**126**	**948**	**948**	**1318**	**7**	**126**	**980**	**980**	**1361**	**11**

Appendix E2: Comparison of the tomato historical IR to mid-century and end-century IR

Historical					Mid-century					End-century				
Year	**Growing cycle length**	**ETc**	**Crop IR**	**Gross IR**	**Growing cycle length**	**ETc**	**Crop IR**	**Gross IR**	**Variation of Gross IR (%)**	**Growing cycle length**	**ETc**	**Crop Irr**	**Gross Irr**	**Variation of Gross Irr(%)**
1981	136	1206	1206	1605	140	1116	1116	1529	-5	144	1131	1131	1601	0
1982	139	966	966	1309	140	1052	1052	1440	10	142	1089	1089	1510	15
1983	137	1064	1064	1431	138	1253	1253	1715	20	138	1298	1298	1776	24
1984	139	1149	1149	1551	140	1326	1326	1812	17	139	1375	1375	1862	20
1985	143	1163	1163	1642	143	1326	1326	1872	14	137	1378	1378	1879	14
1986	137	880	880	1173	144	949	949	1347	15	136	979	979	1292	10
1987	137	901	901	1211	134	944	944	1241	2	137	977	977	1313	8
1988	137	992	992	1318	144	1103	1103	1564	19	139	1141	1141	1546	17
1989	136	1097	1097	1467	138	1303	1303	1775	21	143	1348	1348	1895	29
1990	143	1115	1115	1568	138	1236	1236	1662	6	139	1280	1280	1738	11
1991	135	1075	1074	1419	140	1166	1165	1606	13	136	1206	1205	1603	13
1992	144	1024	1020	1449	136	1169	1165	1574	9	143	1211	1207	1704	18
1993	138	990	990	1344	136	1107	1107	1470	9	137	1144	1144	1538	14
1994	141	944	944	1303	143	982	982	1383	6	143	1010	1010	1423	9
1995	143	916	916	1287	143	963	963	1352	5	140	994	994	1362	6
1996	135	930	930	1224	143	954	954	1345	10	140	983	983	1350	10
1997	138	901	901	1230	143	956	956	1348	10	138	987	987	1351	10
1998	140	917	917	1260	142	992	992	1380	9	144	1023	1023	1447	15
1999	140	827	827	1134	137	870	870	1161	2	143	896	896	1264	12
2000	143	938	938	1319	140	1025	1025	1404	6	142	1059	1059	1480	12
2001	139	922	922	1257	135	962	962	1267	1	140	993	993	1368	9
2002	140	1058	1058	1455	141	1108	1108	1535	5	136	1148	1148	1530	5
2003	138	1107	1107	1498	137	1111	1111	1485	-1	138	1153	1153	1554	4
2004	142	1188	1188	1651	141	1242	1242	1716	4	139	1288	1288	1748	6
2005	140	1166	1166	1591	140	1194	1194	1630	2	142	1239	1239	1724	8
2006	143	1086	1086	1529	143	1118	1118	1573	3	136	1157	1157	1540	1
2007	138	1062	1062	1429	136	1128	1128	1502	5	136	1167	1167	1555	9
2008	139	1028	1028	1395	136	1092	1092	1456	4	140	1130	1130	1549	11
2009	144	979	979	1389	136	958	958	1262	-9	141	990	990	1368	-2
Average	**139**	**1020**	**1020**	**1394**	**140**	**1093**	**1093**	**1497**	**7**	**140**	**1130**	**1130**	**1547**	**11**

Appendix E3: Comparison of the sweet pepper historical IR to mid-century and end-century IR

	Historical				Mid-century					End-century				
Year	**Growing cycle length**	**ETc**	**Crop IR**	**Gross IR**	**Growing cycle length**	**ETc**	**Crop IR**	**Gross IR**	**Variation of Gross IR (%)**	**Growing cycle length**	**ETc**	**Crop IR**	**Gross IR**	**Variation of Gross IR (%)**
1986	149	907	907	1283	149	936	936	1325	3	143	971	971	1293	1
1987	142	752	752	1029	139	740	740	968	-6	142	762	762	1025	0
1988	141	775	775	988	149	788	788	1112	13	143	811	811	1087	10
1989	148	730	730	1025	142	812	812	1082	6	143	834	834	1122	9
1990	146	710	710	981	148	733	733	1031	5	145	756	756	1035	5
1991	142	707	707	951	144	746	746	1013	7	148	769	769	1082	14
1992	147	813	813	1132	141	843	843	1110	-2	147	870	870	1211	7
1993	147	817	817	1137	145	852	852	1164	2	142	879	879	1168	3
1994	140	741	741	971	146	818	818	1128	16	146	844	844	1165	20
1995	149	791	791	1120	143	825	825	1108	-1	146	852	852	1177	5
1996	146	833	833	1146	142	863	863	1152	1	145	891	891	1220	6
1997	149	789	789	1120	141	747	747	988	-12	142	771	771	1029	-8
1999	147	664	664	925	142	685	685	916	-1	146	706	706	976	5
2000	147	665	665	927	149	709	709	1005	8	139	731	731	954	3
2001	141	668	668	890	141	686	686	916	3	142	707	707	951	7
2002	138	678	678	879	147	705	705	982	12	139	727	727	952	8
2003	140	682	682	899	138	678	678	877	-2	145	700	700	964	7
2004	148	697	697	976	146	720	720	995	2	140	741	741	971	-1
2005	144	766	766	1042	142	767	767	1027	-1	143	791	791	1069	3
2006	149	793	793	1125	149	808	808	1146	2	146	833	833	1146	2
2007	141	734	729	971	140	765	759	1008	4	139	789	783	1030	6
2008	145	757	757	1039	142	796	796	1068	3	146	821	821	1137	9
2009	142	749	747	1005	149	724	722	1026	2	145	747	745	1025	2
Average	**145**	**749**	**748**	**1024**	**144**	**771**	**771**	**1050**	**3**	**144**	**796**	**795**	**1078**	**5**

Appendix E4: Comparison of the cabbage historical IR to mid-century and end-century IR

Historical					Mid-century					End-century				
Year	**Growing cycle length**	**ETc**	**Crop IR**	**Gross IR**	**Growing cycle length**	**ETc**	**Crop IR**	**Gross IR**	**Variation of Gross IR (%)**	**Growing cycle length**	**ETc**	**Crop Irr**	**Gross Irr**	**Variation of Gross Irr(%)**
1981	99	665.2	665.2	936.4	96	710.5	710.5	953.3	2	97	739.9	739.9	1007.4	8
1982	96	507.4	507.4	692.1	96	549.7	549.7	747	8	99	567.1	567.1	803.7	16
1983	97	715	715	976.2	98	884.9	884.9	1230.7	26	97	823	823	1140.3	17
1984	99	533.2	533.2	754.1	99	587.3	587.3	831	10	99	606.3	606.3	858.1	14
1985	97	554.7	554.7	764.6	97	589.8	589.8	810.9	6	99	609.9	609.9	861	13
1986	97	502.2	502.2	690.3	95	546.7	546.7	738.8	7	98	565.1	565.1	789.3	14
1987	99	517.4	517.4	732.1	99	533.1	533.1	754.5	3	94	551.2	551.2	733.7	0
1988	99	522.9	522.9	738.2	96	584.6	584.6	791.7	7	99	604.3	604.3	852.9	16
1989	96	665.6	665.6	903.7	96	774.9	774.9	1053.3	17	99	804.7	804.7	1134	25
1990	98	611.8	611.8	851.1	99	649.2	649.2	913.3	7	99	671	671	944.4	11
1991	94	618.2	618.2	831.8	98	661.5	661.5	928	12	95	683.9	683.9	932.1	12
1992	97	671.6	671.6	915.7	97	743.4	743.4	1014.7	11	98	770.2	770.2	1068.7	17
1993	97	632.8	632.8	869.1	98	700.3	700.3	975.1	12	96	726.4	726.4	986	13
1994	97	576.8	576.8	795	98	602.6	602.6	842.4	6	96	624.4	624.4	852	7
1995	95	591	591	798.5	99	622.1	622.1	876.4	10	99	643.7	643.7	906.8	14
1996	98	566.3	566.3	793.5	95	573.9	573.9	776.5	-2	99	592.5	592.5	840.6	6
1997	98	668	668	926.8	97	691.7	691.7	942.8	2	98	716.2	716.2	990.2	7
1998	95	576.1	576.1	763.1	97	601.4	601.4	818	7	98	622.6	622.6	860.9	13
1999	94	631.7	631.7	847.5	97	679	679	938.9	11	99	703	703	991.8	17
2000	99	457.2	457.2	642.5	98	492.9	492.9	678.4	6	97	510.1	510.1	688	7
2001	97	653.4	653.4	896	99	675.5	675.5	952.4	6	97	700.1	700.1	956.7	7
2002	96	622.2	622.2	849.8	98	659.1	659.1	920.6	8	99	683	683	964.7	14
2003	97	587.2	587.2	813.1	96	586.6	586.6	800.8	-2	98	607.3	607.3	850.7	5
2004	97	581.8	581.8	798.5	96	582.1	582.1	790.6	-1	96	601.9	601.9	817.5	2
2005	98	583.2	583.2	805.5	99	615.7	615.7	866.4	8	98	636.9	636.9	883.8	10
2006	97	571.3	571.3	787.9	95	584.8	584.8	784	0	97	604.7	604.7	832.7	6
2007	96	556.5	555.9	751.8	99	592	591.4	831.6	11	99	611.4	610.8	859.2	14
2008	96	561.3	561.3	759.4	99	591.2	591.2	832.7	10	98	611.6	611.6	849.6	12
2009	96	546.6	546.6	743.1	99	547.5	547.5	774.6	4	97	565.8	565.8	781.3	5
Average	**97**	**588**	**588**	**808**	**97**	**628**	**628**	**868**	**7**	**98**	**647**	**647**	**898**	**11**

Appendix E5: Comparison of the onion historical IR to mid-century and end-century IR

Historical					Mid-century					End-century				
Year	**Growing cycle length**	**ETc**	**Crop IR**	**Gross IR**	**Growing cycle length**	**ETc**	**Crop IR**	**Gross IR**	**Variation of Gross IR (%)**	**Growing cycle length**	**ETc**	**Crop IR**	**Gross IR**	**Variation of Gross IR (%)**
1986	149	907	907	1283	149	936	936	1325	3	143	971	971	1293	1
1987	142	752	752	1029	139	740	740	968	-6	142	762	762	1025	0
1988	141	775	775	988	149	788	788	1112	13	143	811	811	1087	10
1989	148	730	730	1025	142	812	812	1082	6	143	834	834	1122	9
1990	146	710	710	981	148	733	733	1031	5	145	756	756	1035	5
1991	142	707	707	951	144	746	746	1013	7	148	769	769	1082	14
1992	147	813	813	1132	141	843	843	1110	-2	147	870	870	1211	7
1993	147	817	817	1137	145	852	852	1164	2	142	879	879	1168	3
1994	140	741	741	971	146	818	818	1128	16	146	844	844	1165	20
1995	149	791	791	1120	143	825	825	1108	-1	146	852	852	1177	5
1996	146	833	833	1146	142	863	863	1152	1	145	891	891	1220	6
1997	149	789	789	1120	141	747	747	988	-12	142	771	771	1029	-8
1999	147	664	664	925	142	685	685	916	-1	146	706	706	976	5
2000	147	665	665	927	149	709	709	1005	8	139	731	731	954	3
2001	141	668	668	890	141	686	686	916	3	142	707	707	951	7
2002	138	678	678	879	147	705	705	982	12	139	727	727	952	8
2003	140	682	682	899	138	678	678	877	-2	145	700	700	964	7
2004	148	697	697	976	146	720	720	995	2	140	741	741	971	-1
2005	144	766	766	1042	142	767	767	1027	-1	143	791	791	1069	3
2006	149	793	793	1125	149	808	808	1146	2	146	833	833	1146	2
2007	141	734	729	971	140	765	759	1008	4	139	789	783	1030	6
2008	145	757	757	1039	142	796	796	1068	3	146	821	821	1137	9
2009	142	749	747	1005	149	724	722	1026	2	145	747	745	1025	2
Average	**145**	**749**	**748**	**1024**	**144**	**771**	**771**	**1050**	**3**	**144**	**796**	**795**	**1078**	**5**

Appendices F: **Simulated crops yields and growing cycle length for historical, mid-century, and end-century time periods based on DSSAT**

Appendix F1: Comparison of the potato historical yield to mid-century and end-century yield.

	Yield (kg/ha)				
Planting dates (DOY)	**Historical Yield**	**Mid-century Yield**	**Variation (%)**	**End-Century Yield**	**Variation (%)**
264	12455	4832	-61	1790	-86
269	11266	4305	-62	1601	-86
274	10217	4340	-58	1623	-84
279	8744	4384	-50	1926	-78
284	7528	4575	-39	2216	-71
289	6996	4410	-37	2131	-70
294	6350	4342	-32	2114	-67
299	6413	4359	-32	2103	-67
304	6619	3454	-48	1424	-78
310	7936	3080	-61	1327	-83
315	8080	2781	-66	1187	-85
320	8399	2702	-68	955	-89
325	8345	2873	-66	964	-88
330	7742	3101	-60	968	-88
335	6995	2194	-69	367	-95
Average	**8272**	**3716**	**-54**	**1513**	**-81**

Appendix F2: Comparison of the tomato historical yield to mid-century and end-century yield –

Average growing season length/period.

	Yield and crop cycle length				
Planting dates (DOY)	**Historical Yield**	**Mid-century Yield**	**Variation (%)**	**End-Century Yield**	**Variation (%)**
264	3883	1911	-51	1002	-74
269	4513	2348	-48	1297	-71
274	5183	2779	-46	1604	-69
279	5862	3269	-44	1948	-67
284	6351	3706	-42	2252	-65
289	6810	4075	-40	2576	-62
294	7162	4435	-38	2837	-60
299	7430	4799	-35	3122	-58
304	7676	5021	-35	3379	-56
310	7835	5216	-33	3562	-55
315	7796	5347	-31	3704	-52
320	7743	5343	-31	3761	-51
325	7590	5253	-31	3709	-51
330	7364	5156	-30	3616	-51
335	7119	4976	-30	3506	-51
Average yield (kg/ha)	**6688**	**4242**	**-38**	**2792**	**-60**
Average crop cycle length (days)	**101**	**94**		**92**	

Appendix F3: Comparison of the sweet pepper historical yield to mid-century and end-century yield –Average growing season length/period

	Yield and crop cycle length				
Planting dates (DOY)	**Historical Yield**	**Mid-century Yield**	**Variation (%)**	**End-Century Yield**	**Variation (%)**
222	8006	6181	-23	5021	-37
232	8837	7034	-20	5747	-35
242	9452	7865	-17	6536	-31
253	10006	8432	-16	7202	-28
263	10088	8659	-14	7453	-26
273	9840	8577	-13	7445	-24
283	9341	8389	-10	7220	-23
293	8704	7875	-10	6768	-22
303	7989	7249	-9	6185	-23
314	7065	6404	-9	5422	-23
324	6138	5525	-10	4641	-24
334	5352	4705	-12	3906	-27
Average yield (kg/ha)	**8401**	**7241**	**-14**	**6129**	**-27**
Average crop cycle length (days)	**155**	**153**		**155**	

Appendix F4: Comparison of the cabbage historical yield to mid-century and end-century yield –Average growing season length/period

	Yield and crop cycle length				
Planting dates (DOY)	**Historical Yield**	**Mid-century Yield**	**Variation (%)**	**End-Century Yield**	**Variation (%)**
264	9963	9618	-3	9062	-9
269	9749	9427	-3	8912	-9
274	9686	9147	-6	8839	-9
279	9569	9377	-2	8715	-9
284	9501	9340	-2	8669	-9
289	9526	9376	-2	8640	-9
294	9475	9003	-5	8541	-10
299	9510	9298	-2	8495	-11
304	9596	9321	-3	8515	-11
310	9585	9307	-3	8469	-12
315	9619	9376	-3	8315	-14
320	9673	9392	-3	8142	-16
325	9730	9300	-4	7929	-19
330	9843	9087	-8	7762	-21
335	9867	8927	-10	7541	-24
Average yield (kg/ha)	**9659**	**9286**	**-4**	**8436**	**-13**
Average crop cycle length (days)	**97**	**103**		**113**	

VITA

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Frequent poor harvests in rainfed agriculture have resulted in recurring food shortages in Niger for decades. The predicted climate change during this century is expected to worsen the situation. Dry season irrigated horticulture has been adopted as a coping strategy. However, improved management technologies are necessary for farmers and others in the agricultural system to adapt to water scarcity and the adverse effects of future climate change. The present study investigated the irrigation requirements and the optimum planting periods for cabbage, potato, tomato, onion, and sweet pepper at Niamey, Bonkoukou, Keita, Galmi, and Diffa, respectively, using the DSSAT and CROPWAT models. Predicted climate data from 16 General Circulation Models included in the ClimateWizard program have been used with those crop models to analyze the impacts of the future climate change on the irrigation requirements and the crop yield.

The average daily irrigation water requirements based on the climatic normal period 1981-2010 were estimated to be 8 mm for potato, tomato, and cabbage; and 6 mm for onion and sweet pepper. Based on the predicted temperature increases, the seasonal irrigation water needs will increase by 7% by mid-century and 11% by end-century for cabbage, potato, and tomato. Lesser increases were found for the sweet pepper and onion irrigation water needs with respectively 2% and 3% for mid-century, and 7% and 5% for end-century. The yield of all the five crops is expected to decrease progressively by the mid-century (2050) and end-century (2100) timelines. Tomato and potato yield were found to be the most impacted, including a possible total loss of the potato tuber yield by the end of the century.

The results showed that early November would be the optimum planting periods for cabbage, tomato, and potato in terms of lower crops irrigation water needs and maximum potential yield. While for sweet pepper and onion, transplanting the seedlings in the early September would be a good management strategy.

The suggested adaptation measures to climate change include the development of heat-tolerant varieties, the promotion of rainy season vegetable growth, the switching to other cropping systems in areas where heat sensitive crops will be difficult to grow, extension of onion and sweet pepper to other locations of the country.

ADVISER’S APPROVAL: Dr. Glenn O. Brown